Con-X Science Objectives: Stellar Endpoints

- Galactic Black Holes Binaries:

  Broad Fe Kα line spectroscopy; measure line profiles, constrain black hole spin (if masses known), disk inner edge, couple with fast timing (HXTS, if possible), polarimetry ??

  XTE J1650-500; V4641 Sgr (Miller et al. 2002).

  XTE J1908+094, SAX J1711.6-3808 (in ‘t Zand et al. 2002).

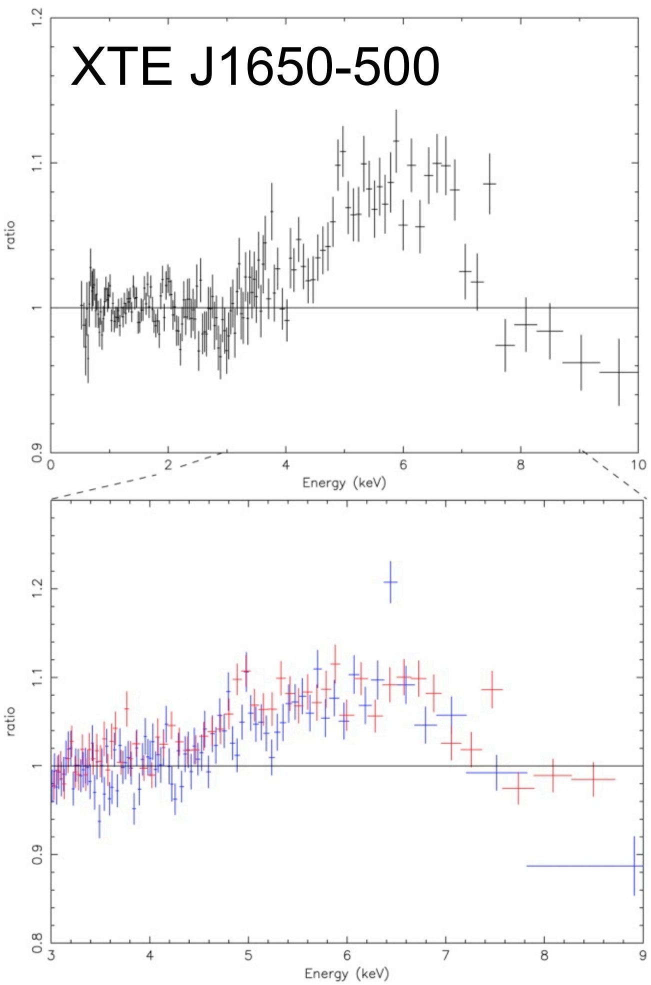
  GRO J1655-40, GRS 1915+105, Cyg X-1

  Fluorescence features from donors; obtain radial velocity information. Strength of features uncertain.

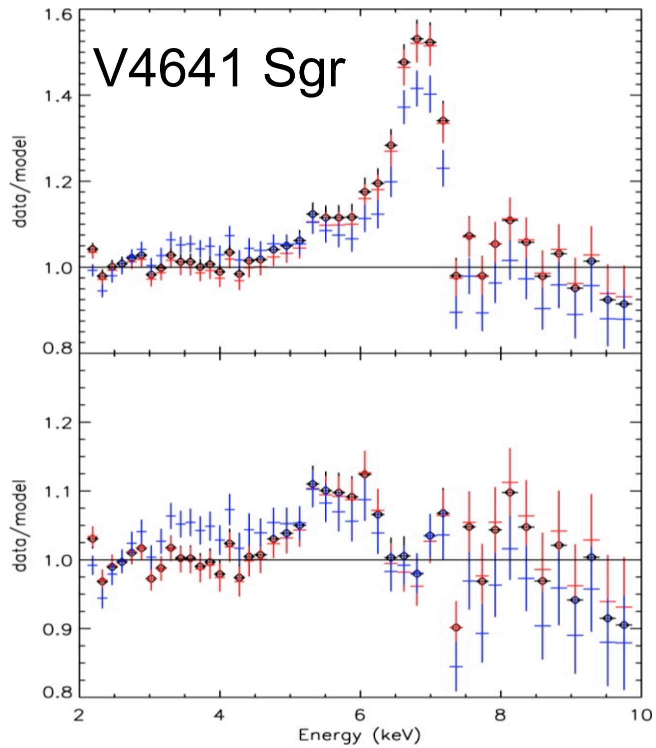
  Spectroscopy of BH’s in quiescence, broad band, coupled with optical, infrared and radio. Extent of accretion disk; ADAFs, event horizon.

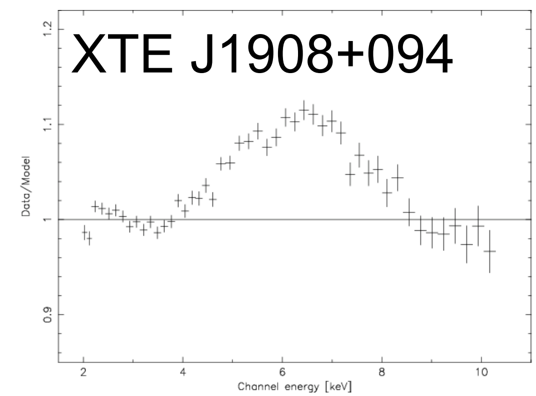
Relativistic Fe Kα Lines from Galactic Black Hole Binaries

Miller et al. 2002



Miller et al, 2002





In ‘t Zand et al. 2002

- Broad, asymmetric lines, thought to be reflection features from inner disk, probes curved space-time near black hole event horizon. Gravitational redshift and relativistic beaming important.

Con-X Science Objectives: Stellar Endpoints

- Accreting Neutron Star Binaries: Big payoff would come from deriving constraints on neutron star M and R, fundamental physics (EOS of dense matter; nucleon interactions).

Spectral lines during X-ray bursts (XMM observations of EXO 0748, Cottam et al. 2002).

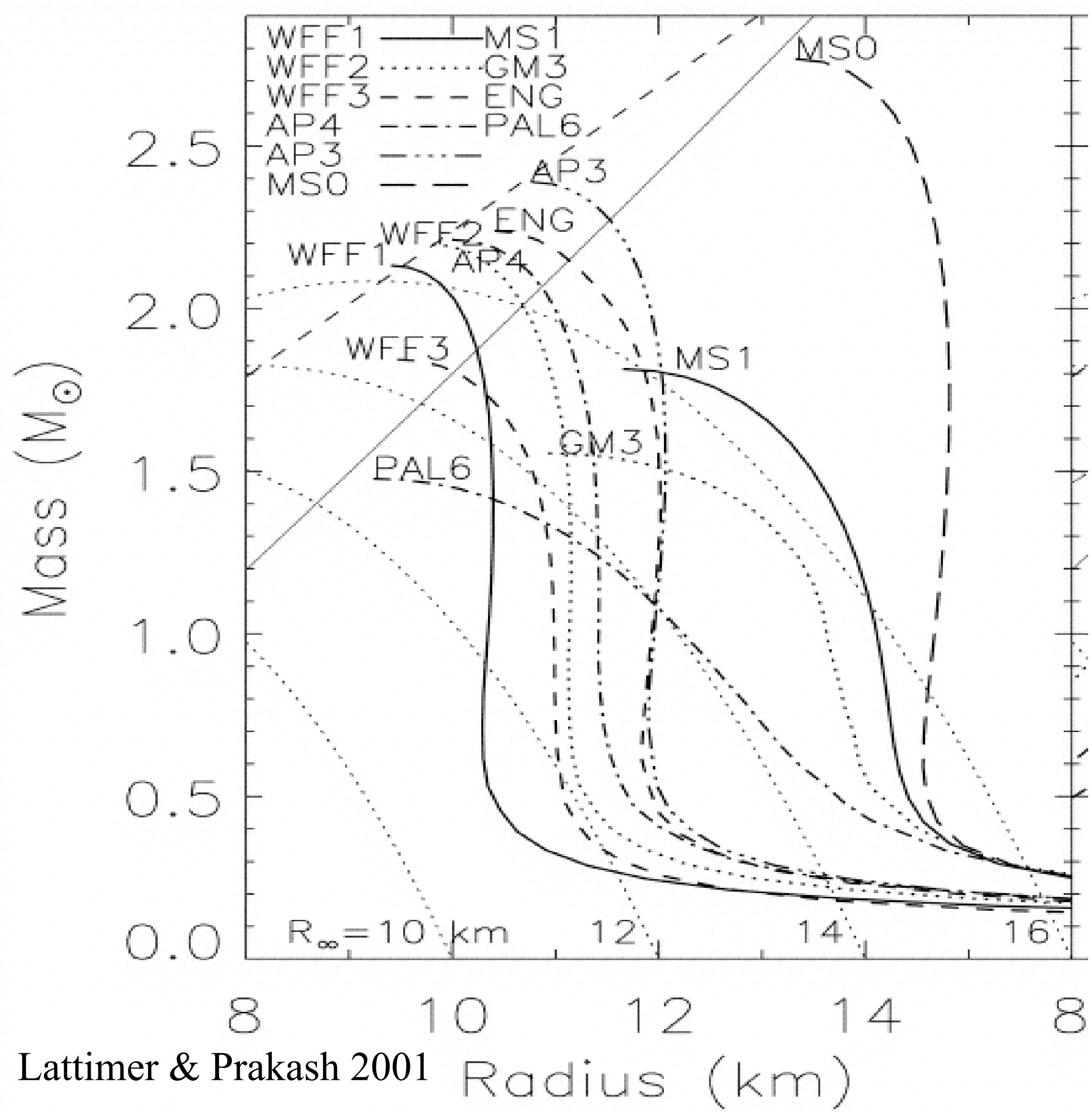
Accretion provides continuous supply of metals, which may settle quickly out of non-accreting neutron stars.

We are starting to see line features! Follow-up observations of recently discovered lines with Constellation-X will confirm them and provide the higher quality data for detailed study and firm identifications of the features.

Pulse phase spectroscopy and timing of X-ray bursts, burst oscillations, as in XTE J1814-338 (Strohmayer et al. 2003, Bhattacharyya et al. 2004).

Superbursts; high resolution spectroscopy, need fast TOO.

Fundamental Physics: The Neutron Star Equation of State (EOS)

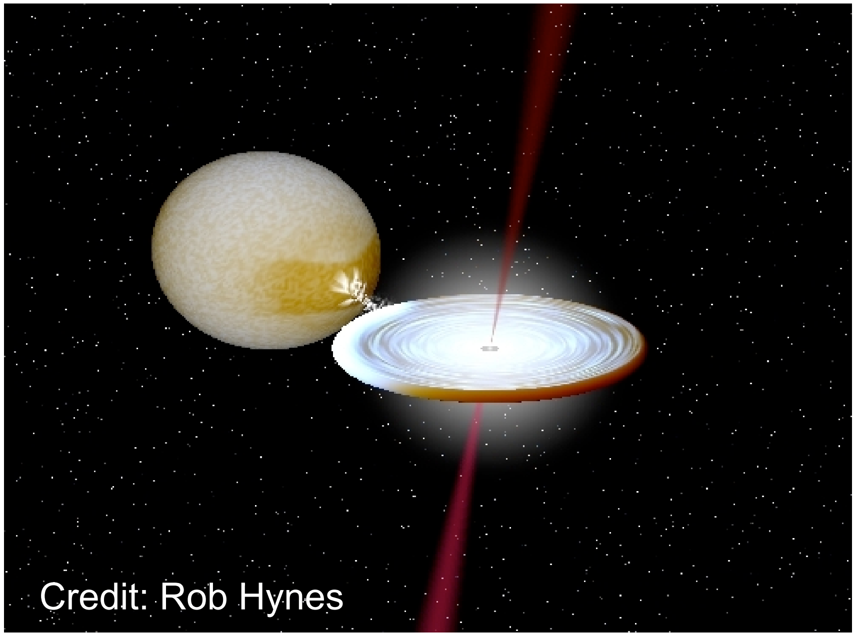


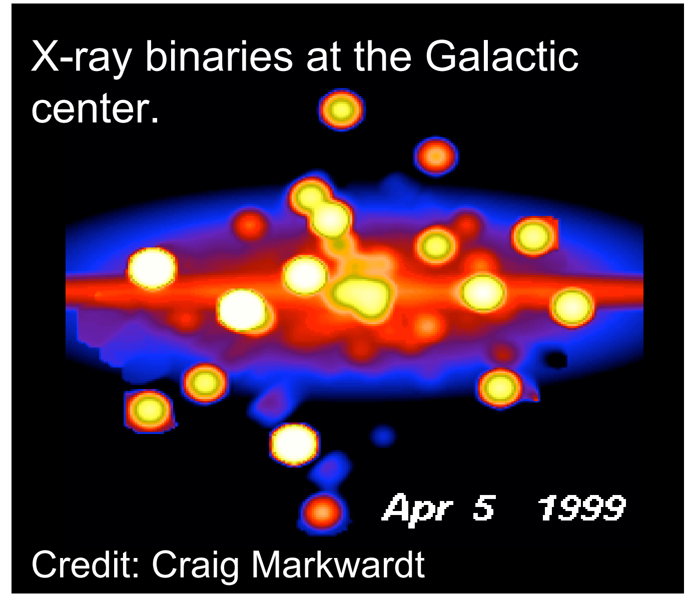
Lattimer & Prakash 2001

$$dP/dr = -\rho\, G\, M(r) / r^2$$

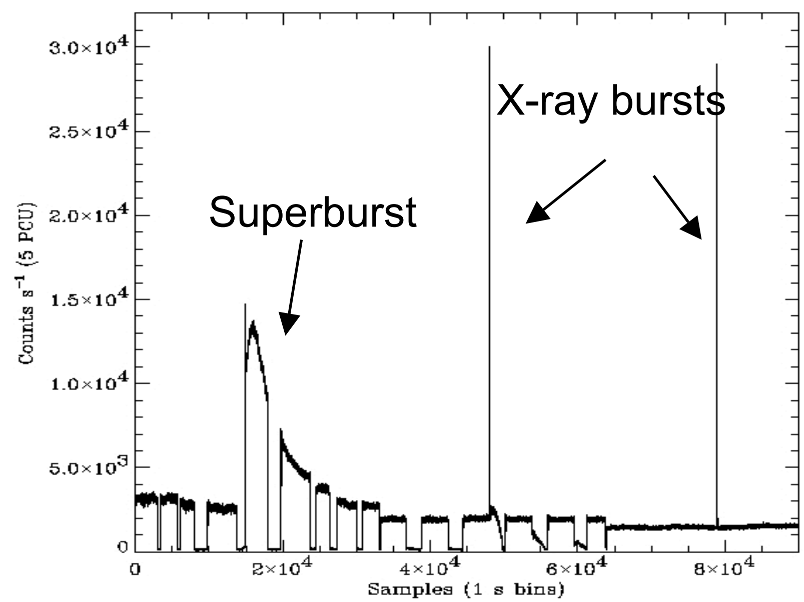
- Maximum mass measurements, limits softening of EOS from hyperons, quarks, other "exotica".
- High mass limit sets highest possible density achievable in neutron stars (thus, in nature, "the MOST dense").

Accreting Neutron Star Binaries





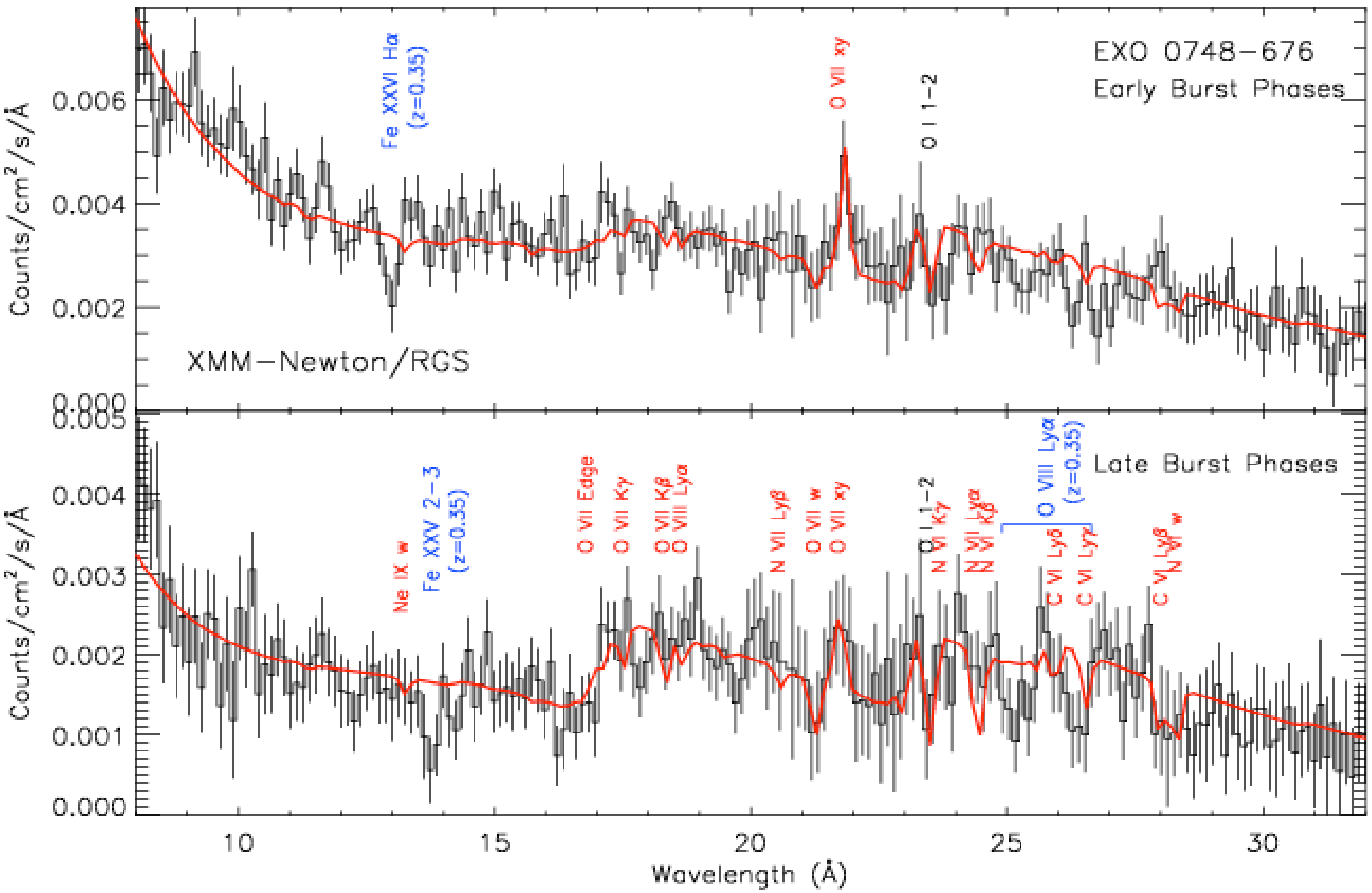
- Accretion supplies metals to NS atmosphere, favors formation of spectral lines.
- Thermonuclear burning of accreted matter produces X-ray bursts.
- NS surface emission visible during X-ray bursts.



X-ray Spectroscopy of Neutron Stars: Recent Results

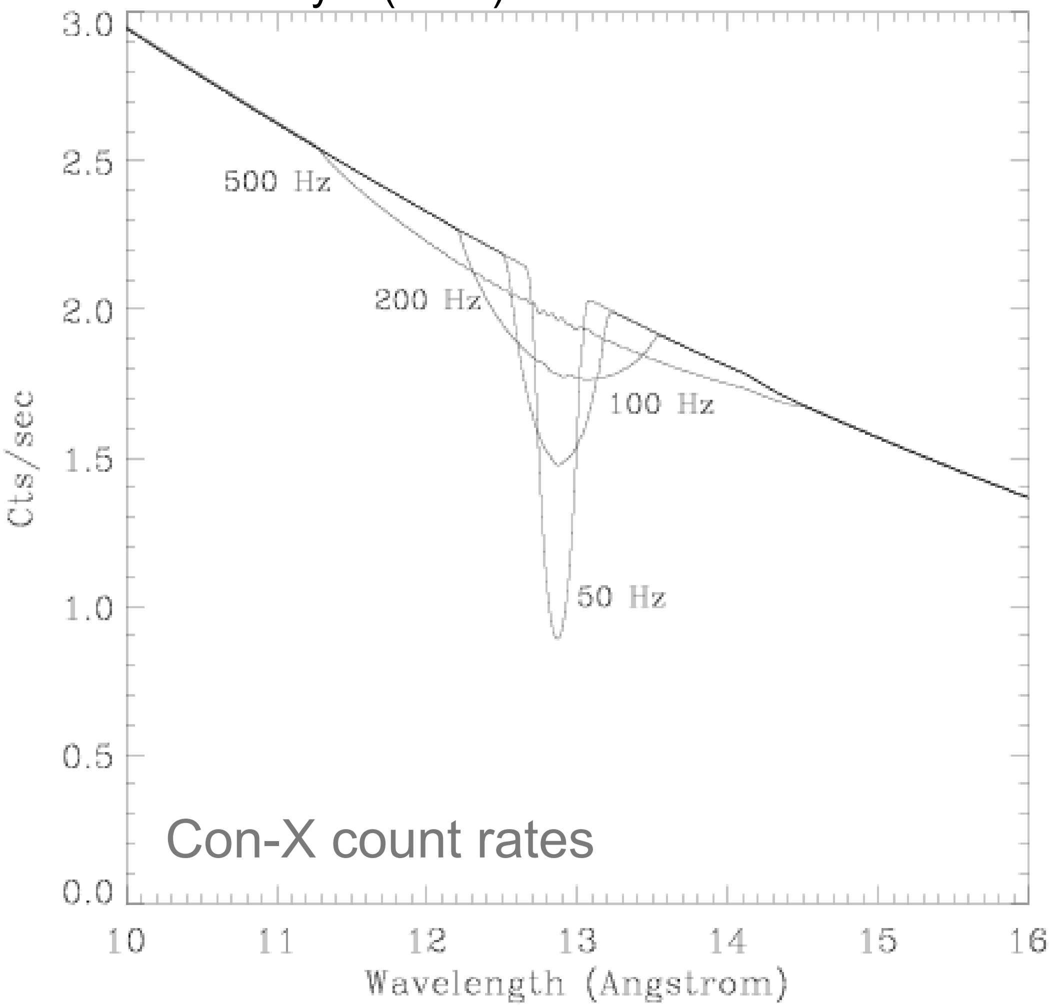
- Recent observations with Chandra, XMM, and RXTE have provided strong evidence for line features from some neutron stars.

XMM/Newton grating observations of X-ray bursts from an accreting neutron star (EXO 0748-676); Cottam, Paerels, & Mendez (2002); Nature



Line Spectroscopy and M - R Constraints for Neutron Stars

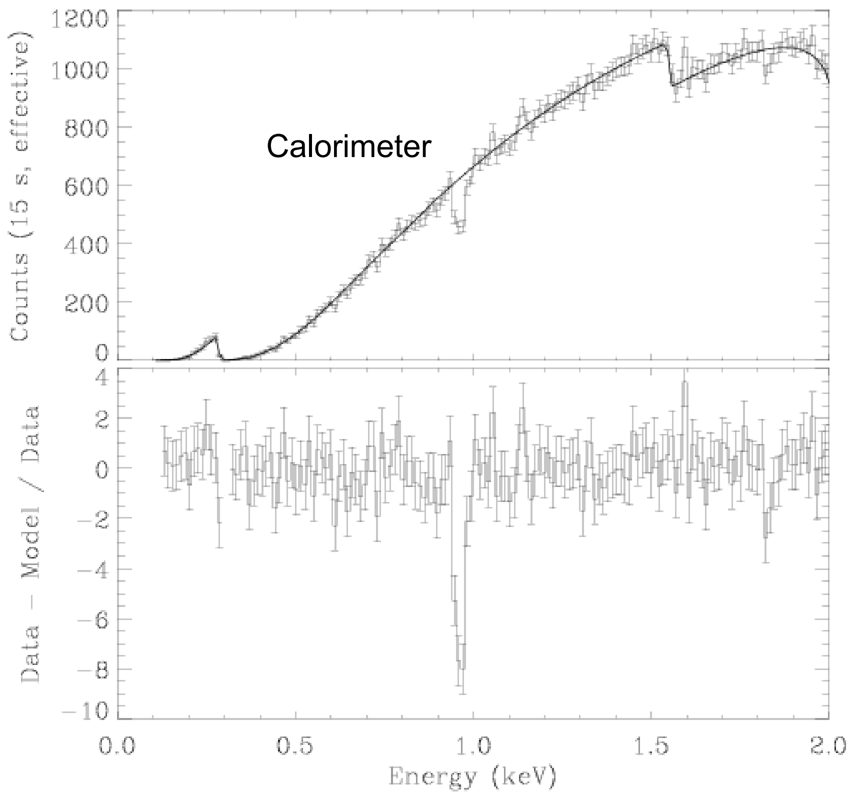
Strohmayer (2003)

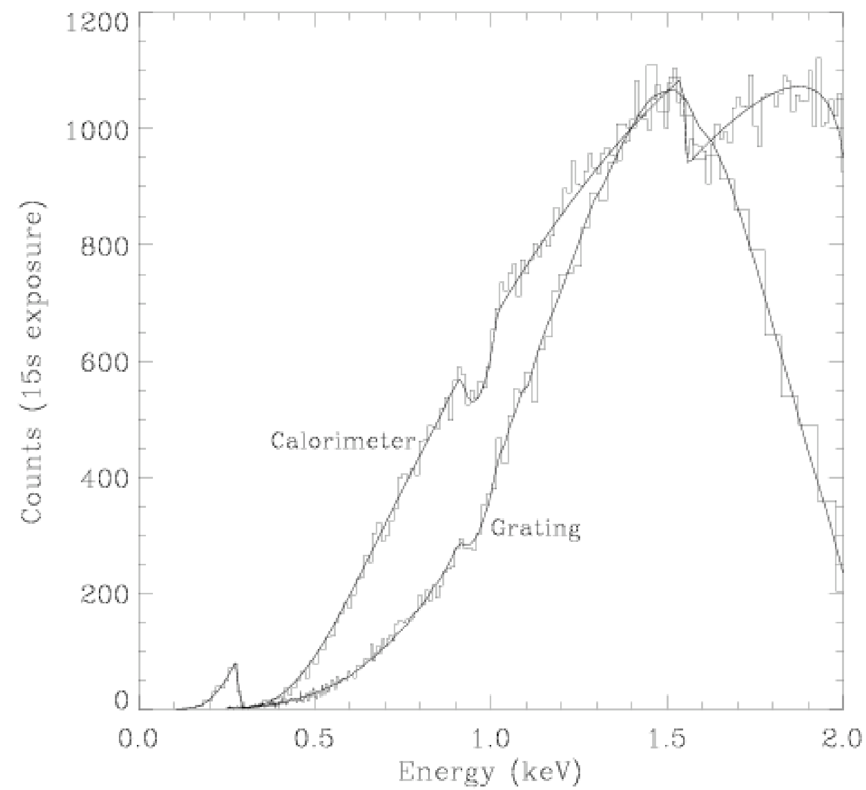


- Lines features from NS surface will be broadened by rotational velocities.
- For many sources, the rotational broadening will dominate (for example, Stark broadening).
- For known spins, velocity gives radius information.
- Asymmetric and double-peaked shapes possible, can constrain emitting surface.

Ozel, Psaltis, Datta, Kapoor, Bildsten, Chang, Paerels.

Simulations of EXO 0748 absorption lines, Con-X area and resolution

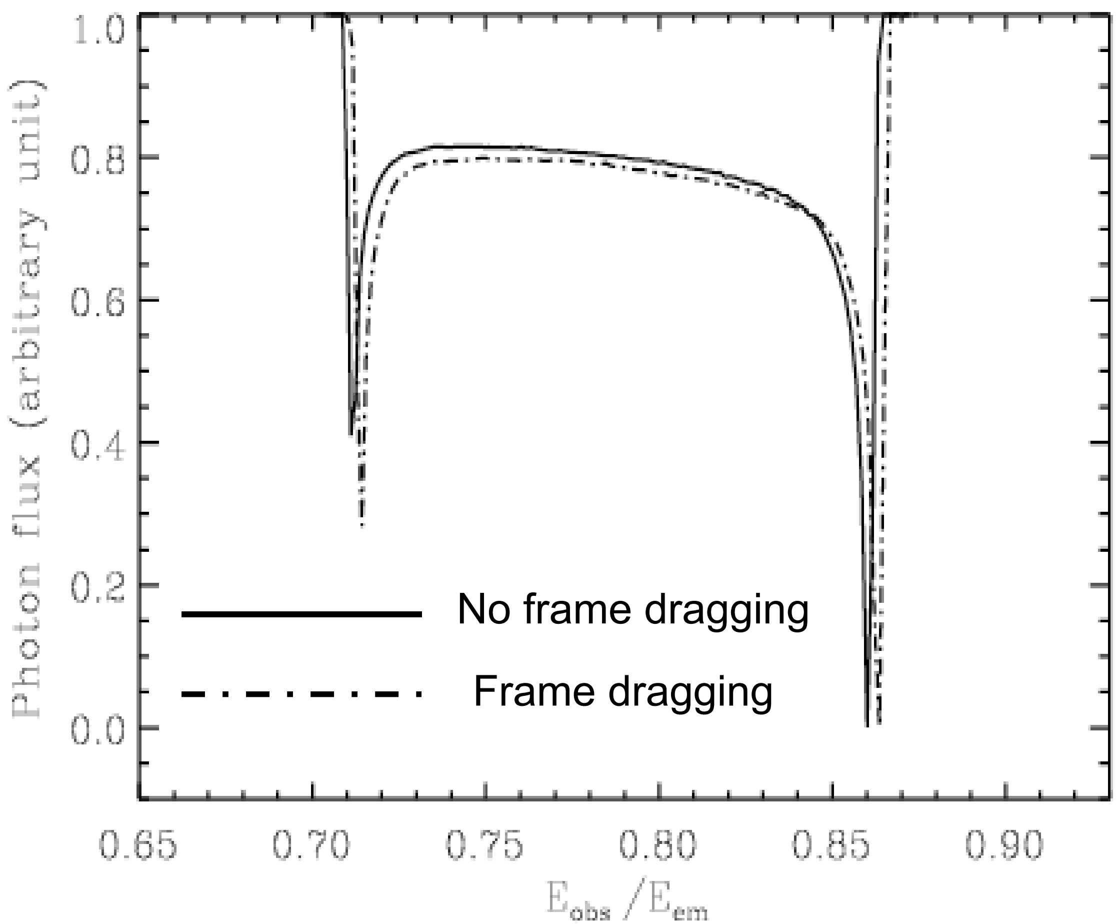




R = 12 km, ν_{spin} = 100 Hz   R = 12 km, ν_{spin} = 200 Hz

- 10 ev EW lines can, in principle, be detected, with Con-X area in single or ~few bursts.

Spectral Line Profiles: Probing Frame Dragging Around a Neutron Star

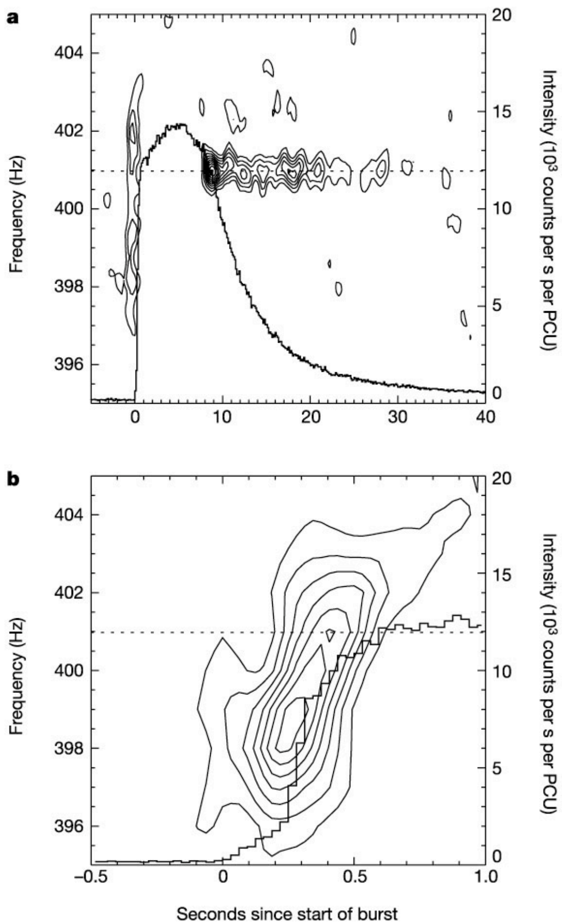


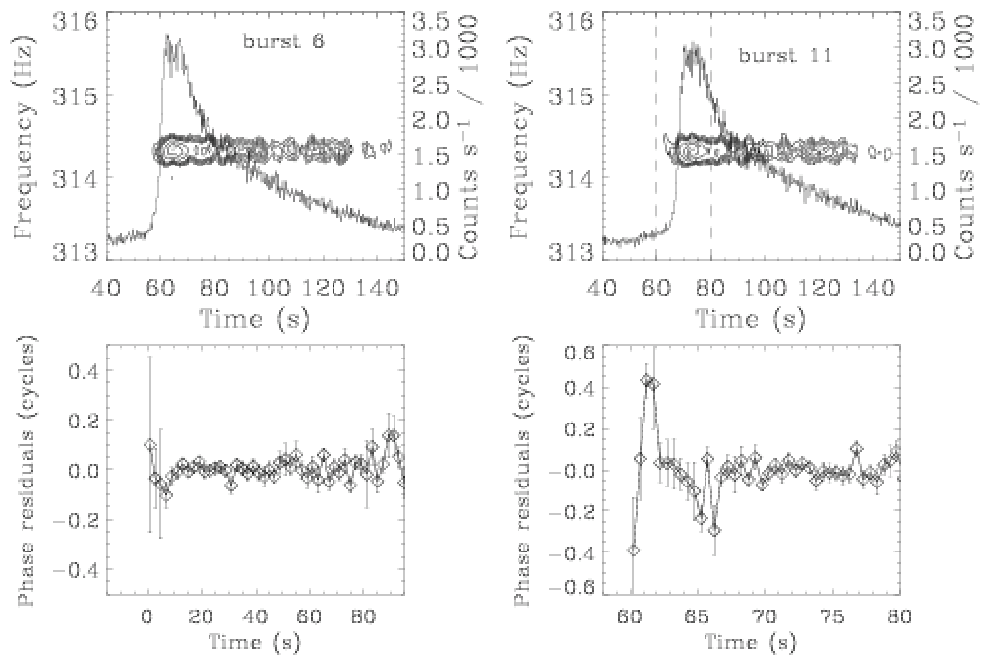
Credit: Bhattacharyya, Miller & Lamb (2003)

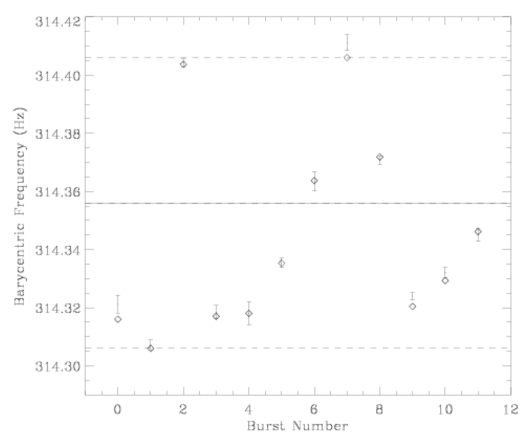
- Accreting neutron stars in binaries spinning at ~300 - 600 Hz.
- v_{rot} ~ 0.1c at surface!
- Linewidth dominated by rotation. Measurement of width can constrain R.
- Double peaked profile when fraction of NS surface emitting (as during burst oscillations).
- Relative depth of two peaks is sensitive to frame dragging term (Bhattacharyya, Miller & Lamb 2003).

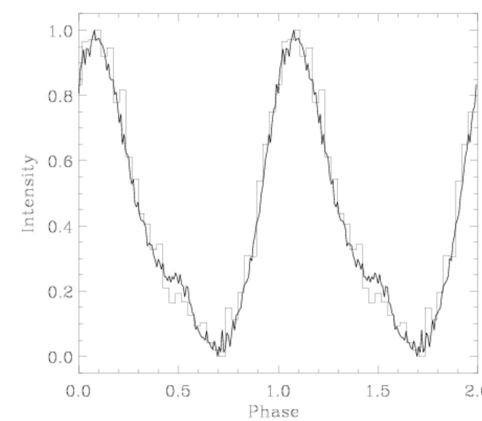
X-ray Bursts from Accreting ms Pulsars: SAX J1808 and XTE J1814

XTE J1814-338: Strohmayer et al. (2003)



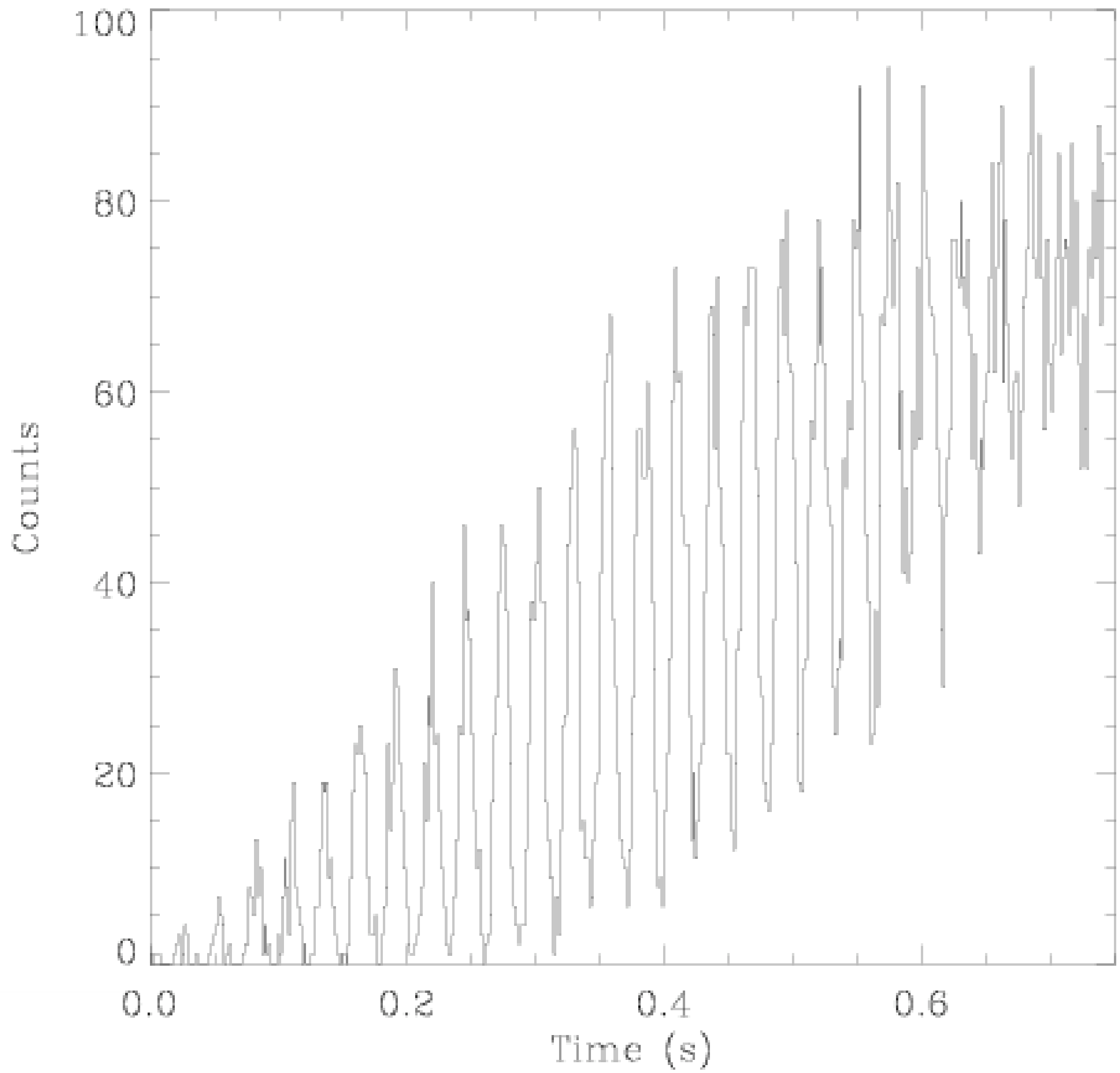






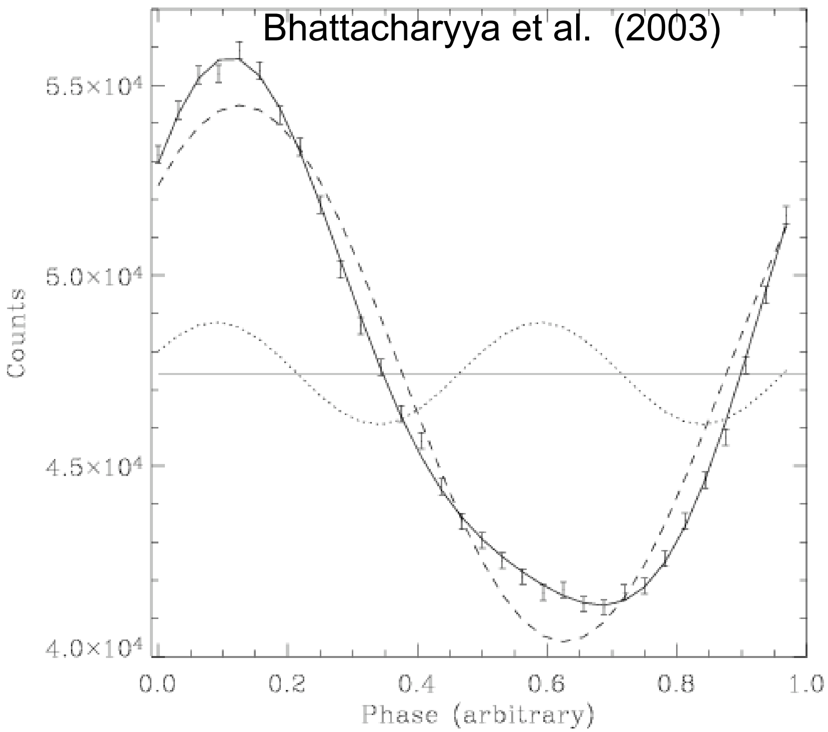
SAX J1808: Chakrabarty et al. (2003)

Burst Oscillations: Simulated Con-X Lightcurve

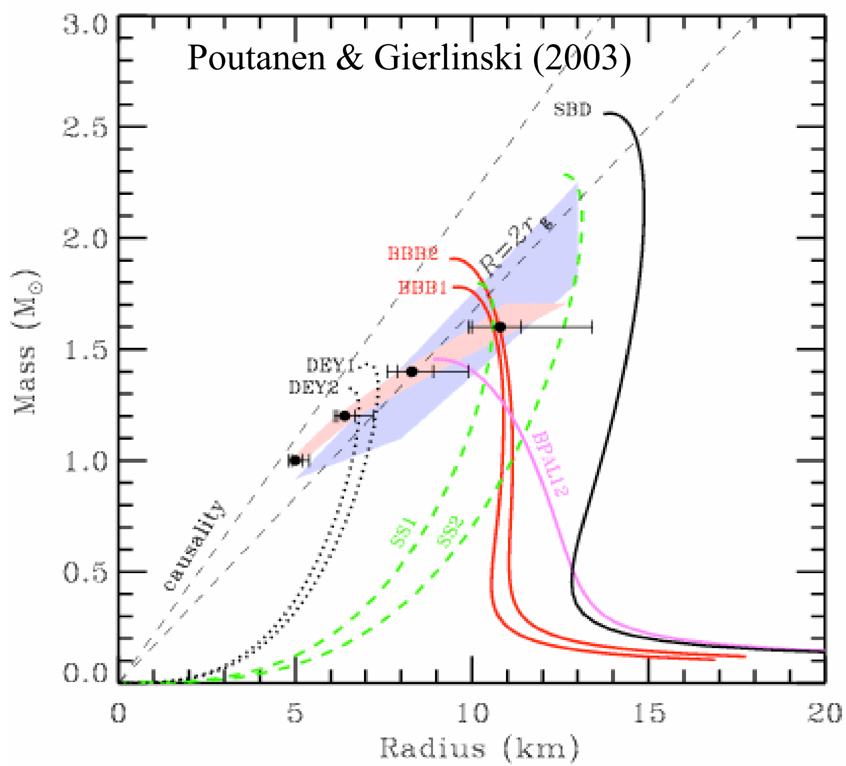


- Use blackbody emission from Neutron star surface.
- Circular hot region which grows linearly with time.
- Flux and spin rate (582 Hz) for bursts from 4U 1636-53.

Mass – Radius Constraints: Recent Results

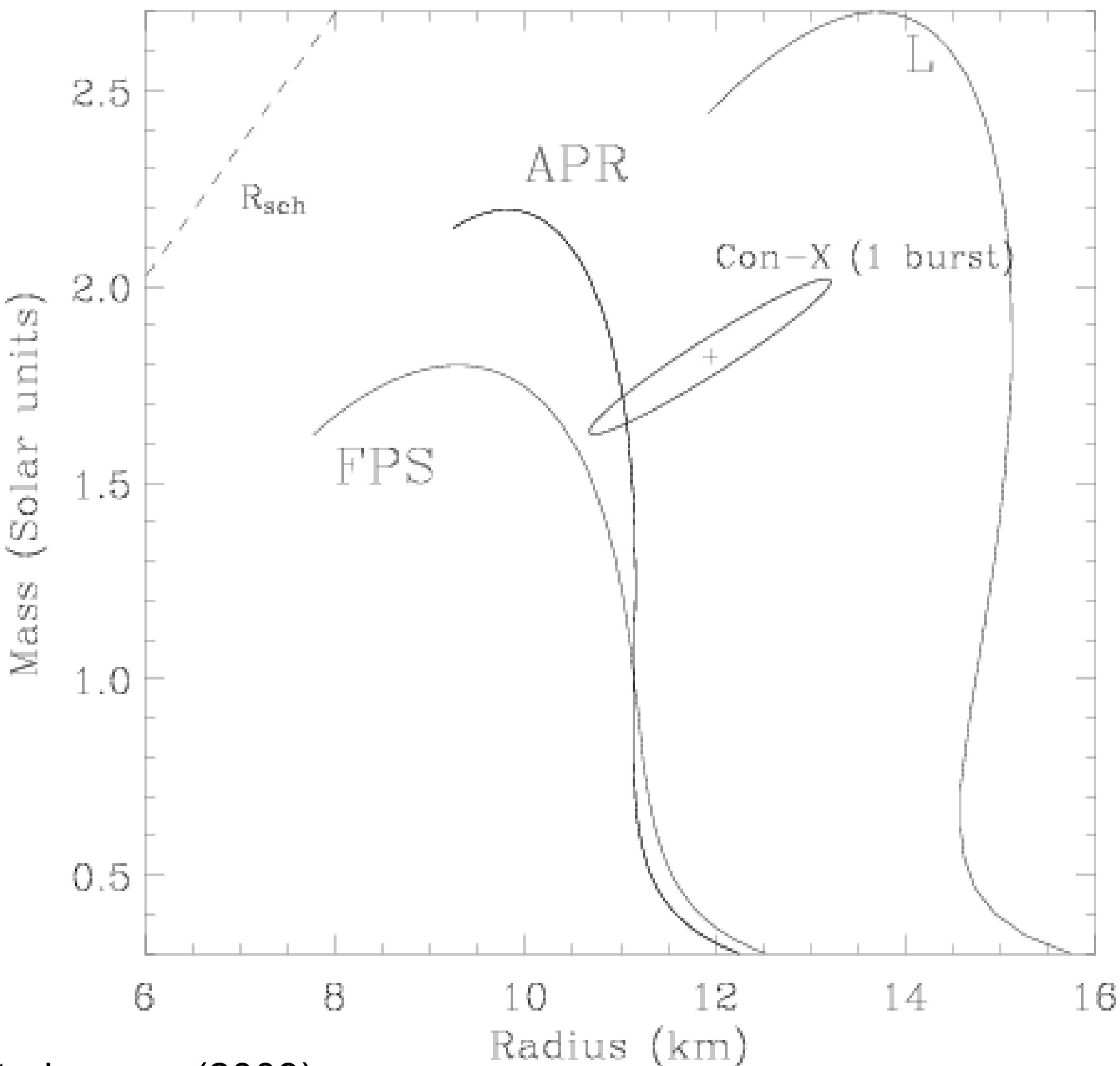


- Comparison of constraints from SAX J1808.4-3658 (Poutanen & Gierlinski 2003, red), and XTE J1814-338 (Bhattacharyya et al. 2004, blue).
- Encouraging overlap of allowed regions



- 27 X-ray bursts from XTE J1814-338 (ms pulsar).
- High signal to noise burst oscillation profiles, with first ever harmonics.

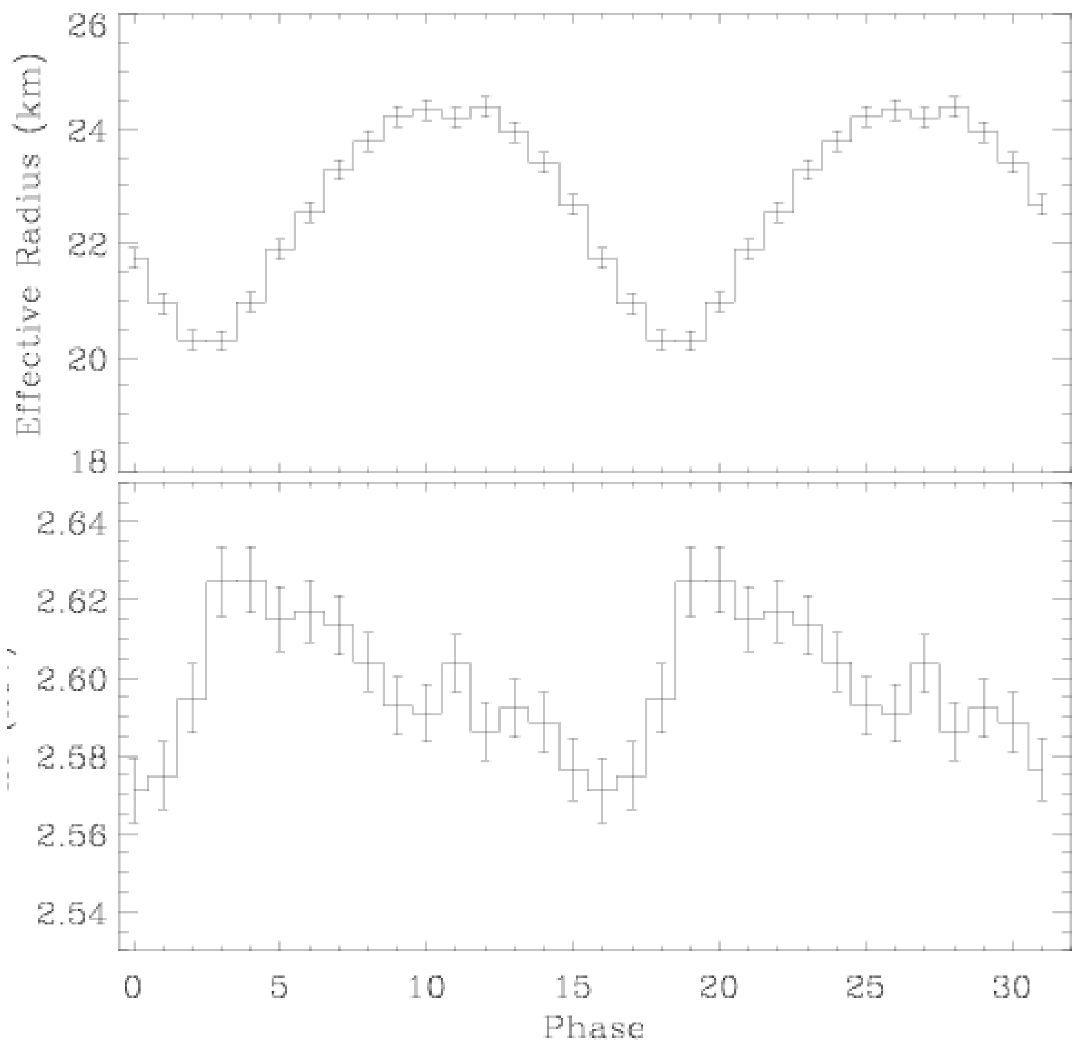
Burst Oscillations and M - R Constraints for Neutron Stars



Strohmayer (2003)

- Pulse shapes of burst oscillations encode information on the neutron star mass and radius.
- Modulation amplitude sensitive to compactness, M/R.
- Pulse sharpness (harmonic content) sensitive to surface velocity, and hence radius for known spin frequency.
- Geometry and evolution of the hot region can be a complicating factor.
- Statistical limits for future missions look promising.

Pulse Phase Spectroscopy: Seeing the Surface Velocity.



- Simulation for J1814-like burst, with 10x RXTE/PCA.
- The rotational doppler shift can be seen in the phase dependence of the fitted kT.
- Could provide a measurement of radius.

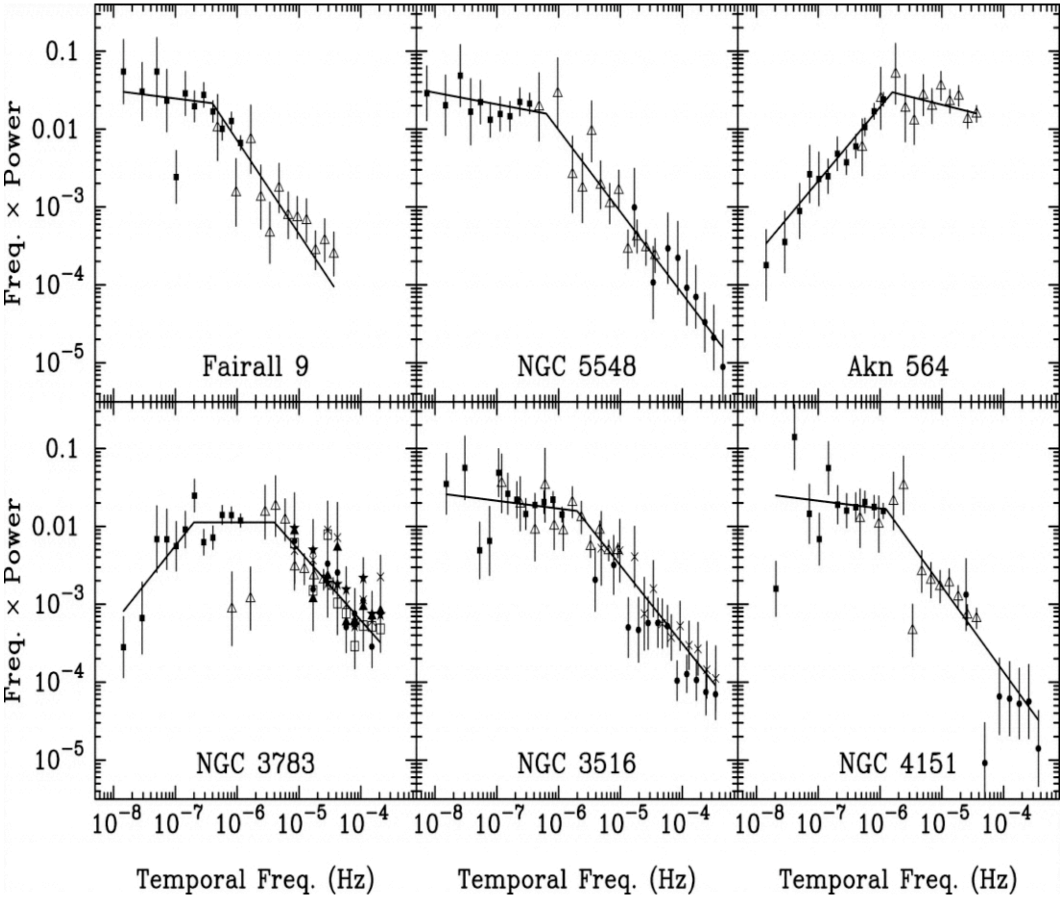
Con-X Science Objectives: Stellar Endpoints

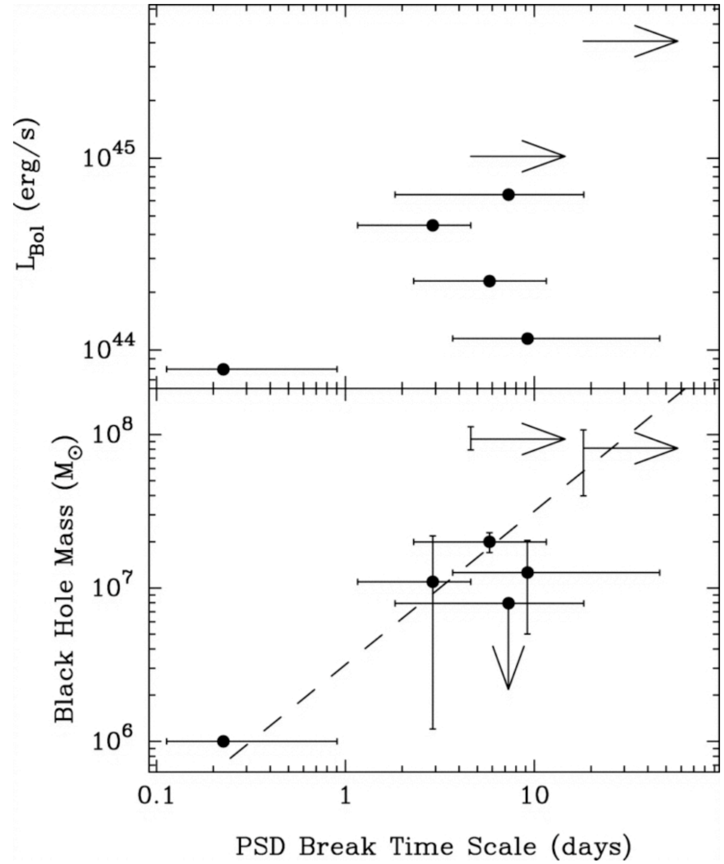
- Extragalactic Black Holes (not AGN): Nature of ULXs, X-ray timing and spectral constraints on ULX's in nearby galaxies.

Constrain M using timing signatures, QPOs (as in M82 ULX), and PSD breaks (Cropper et al.).

Broad band and Fe line spectroscopy to constrain M and a.

Mass Estimates From Power Spectral Measurements

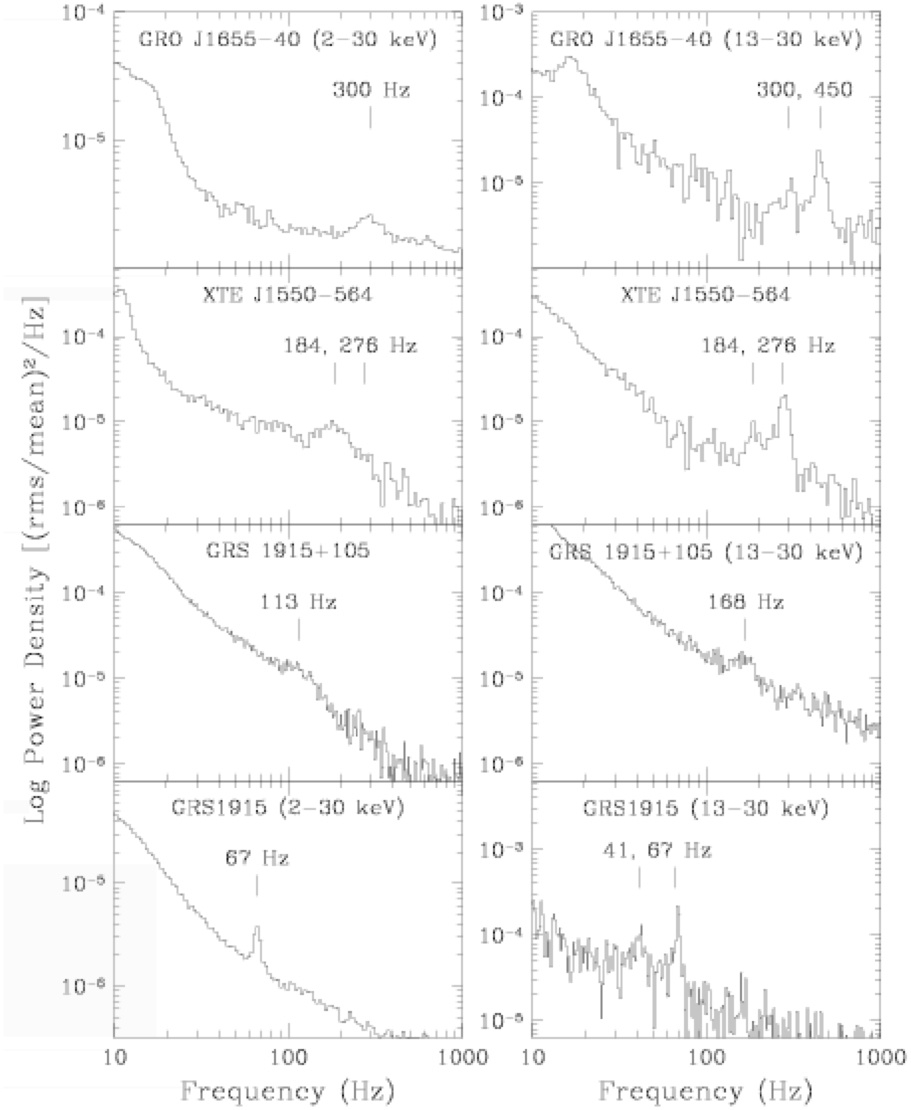




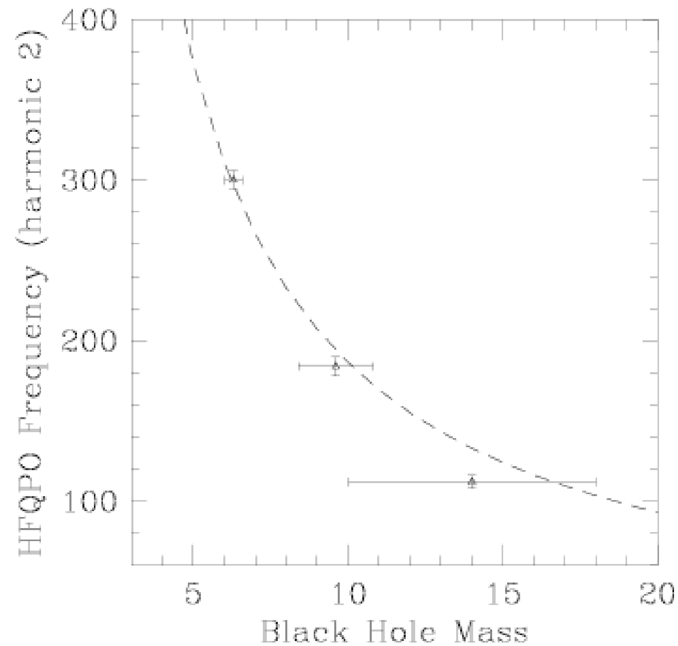
Markowitz et al 2002

- From RXTE monitoring, indications of breaks in PDS of AGN.
- Comparisons with GBH suggest M^{-1} scaling of break frequency.

Black Hole High Frequency QPOs

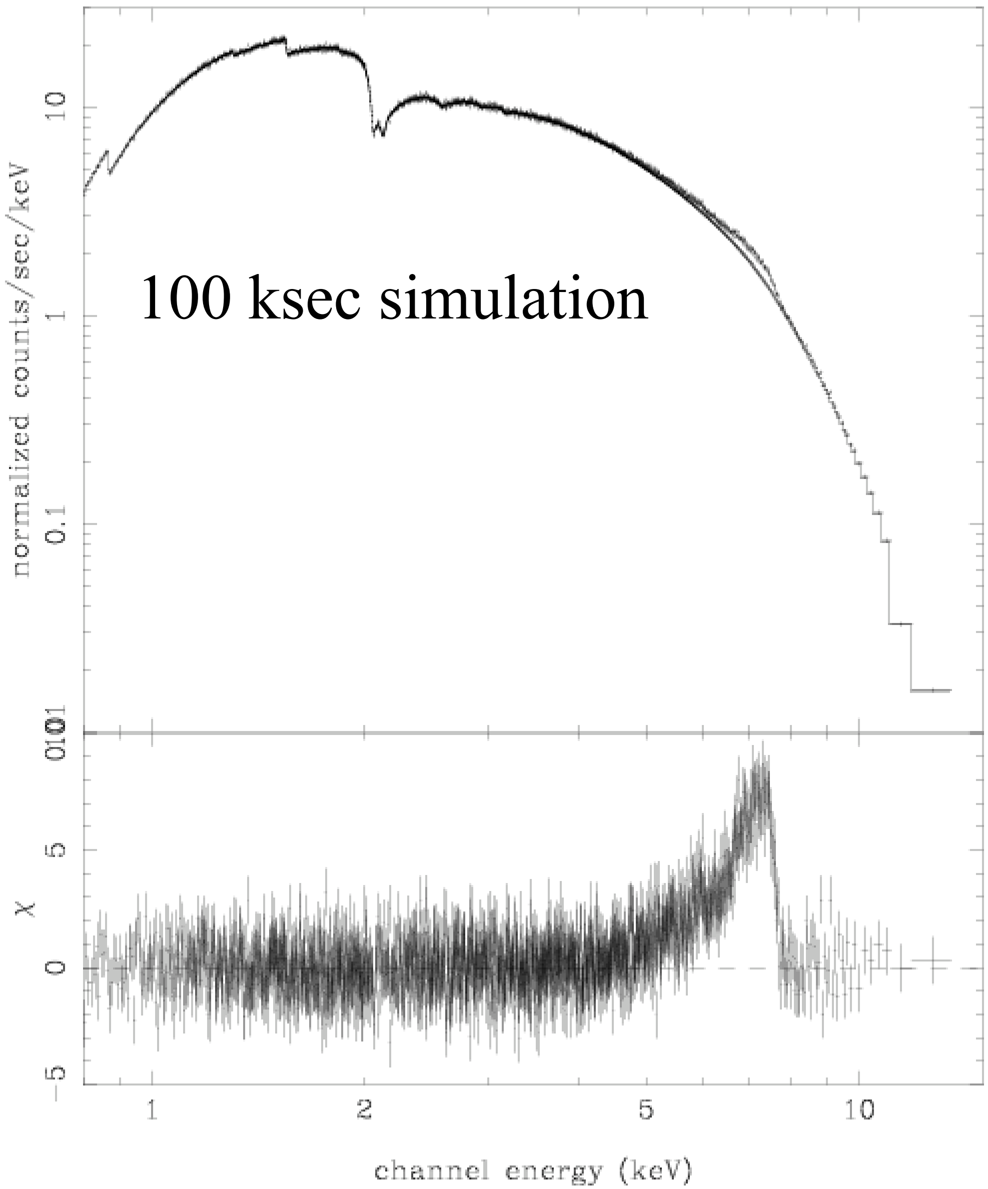


McClintock & Remillard 2003



- ν_{kep} = 220 Hz (M / 10 M_{sun})$^{-1}$
- Frequencies in 3:2 ratio in 3 sources.
- Consistent with M^{-1} scaling.

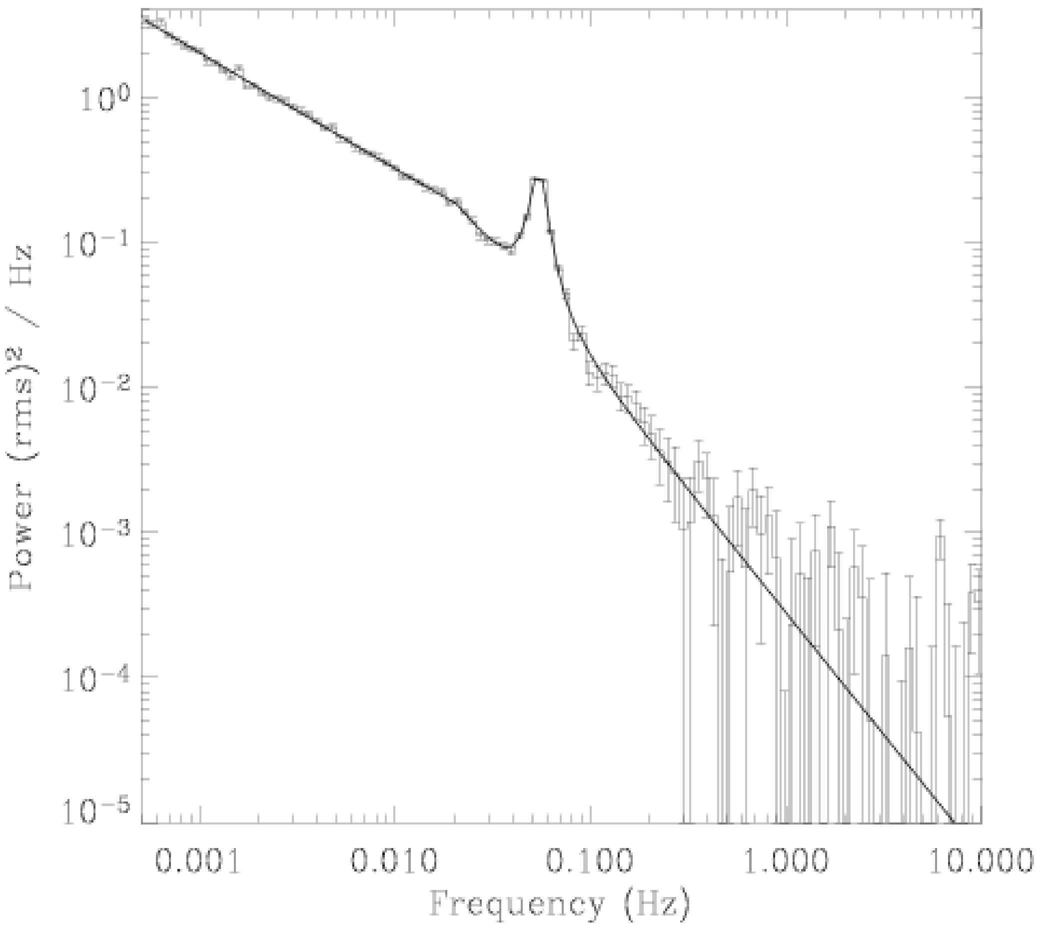
Future Capabilities: Constellation-X Timing and Spectroscopy



- To break new ground need higher countrates.
- Constellation-X should be able to make big leap in both spectroscopy and timing.
- Angular resolution could be an issue for some sources.
- Could enable first population studies, for example, a sample of PDS's for individual galaxies.

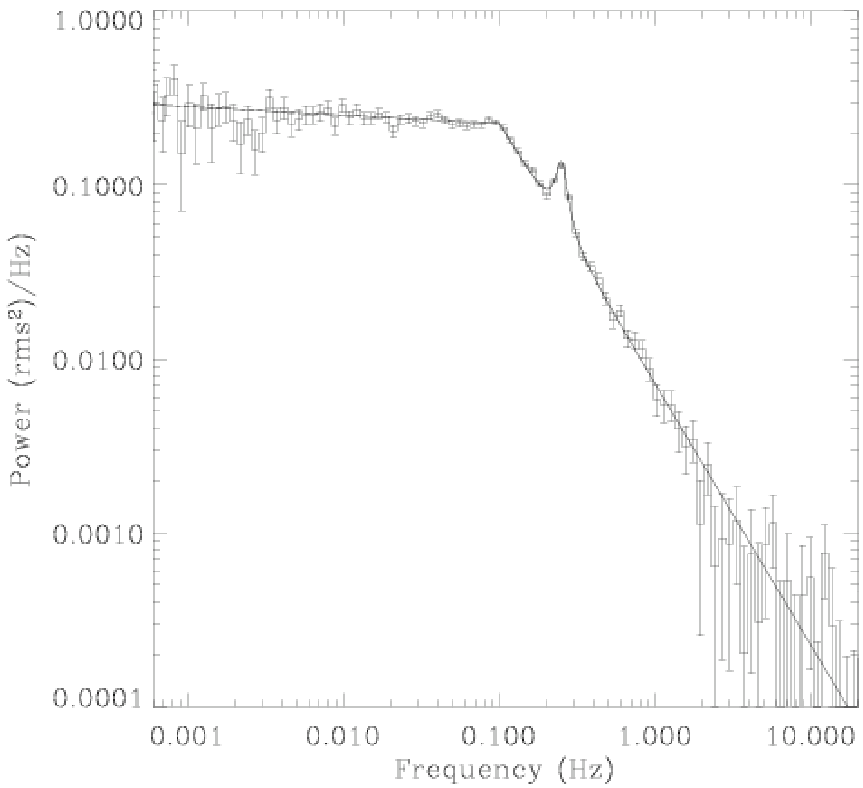
Con-X Simulation for M82 QPO ULX

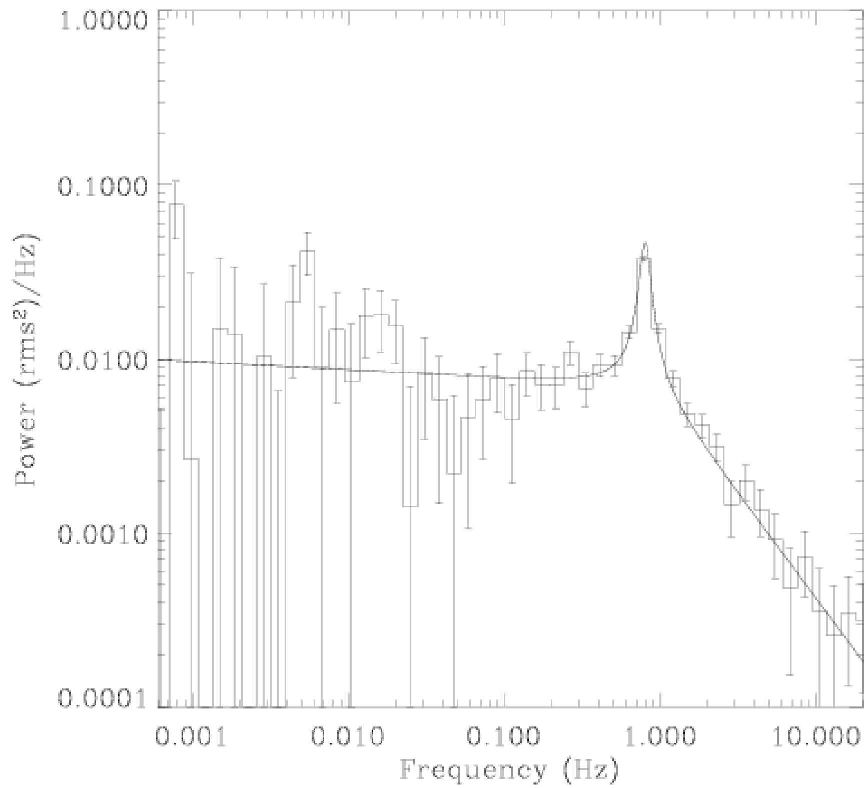
100 ksec, M82 ULX



- Higher S/N broad band power spectrum
- Con-X will be very sensitive to PDS break in the 0.001 to 0.1 Hz range.
- Can do much more precise ‘state’ identifications.
- QPO sensitivity above 1 Hz.

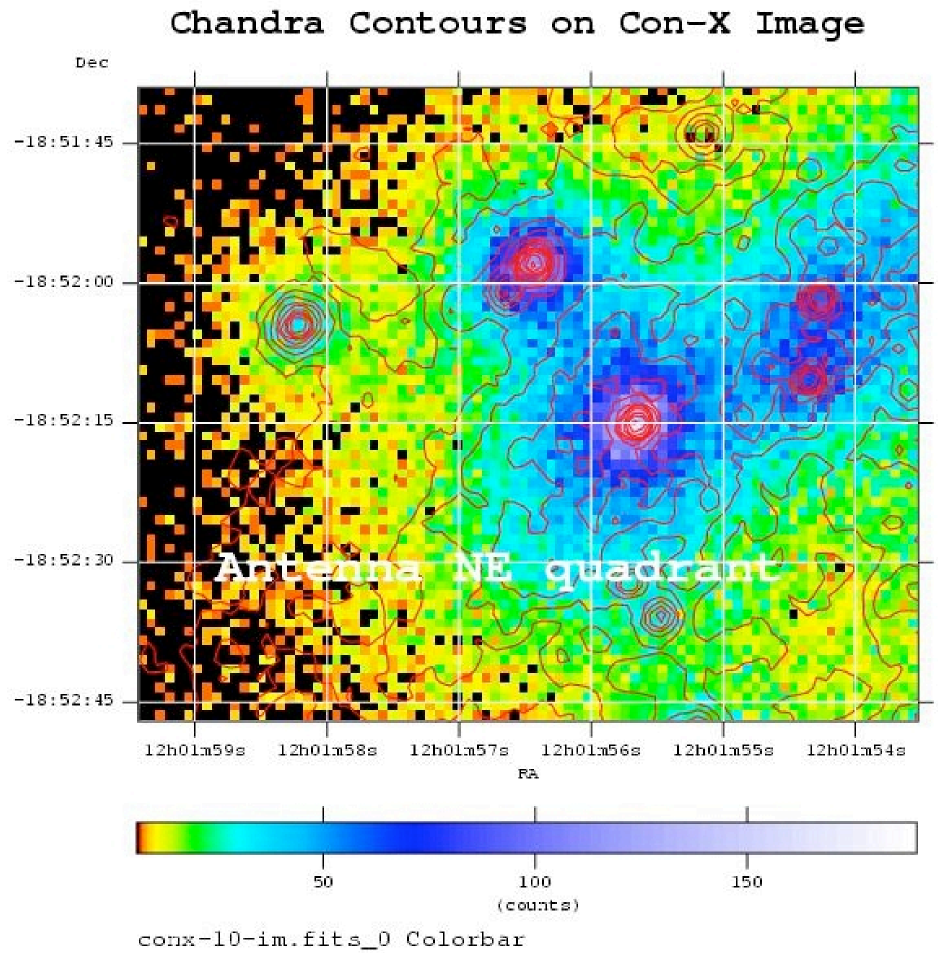
Future Capabilities: Constellation-X Timing

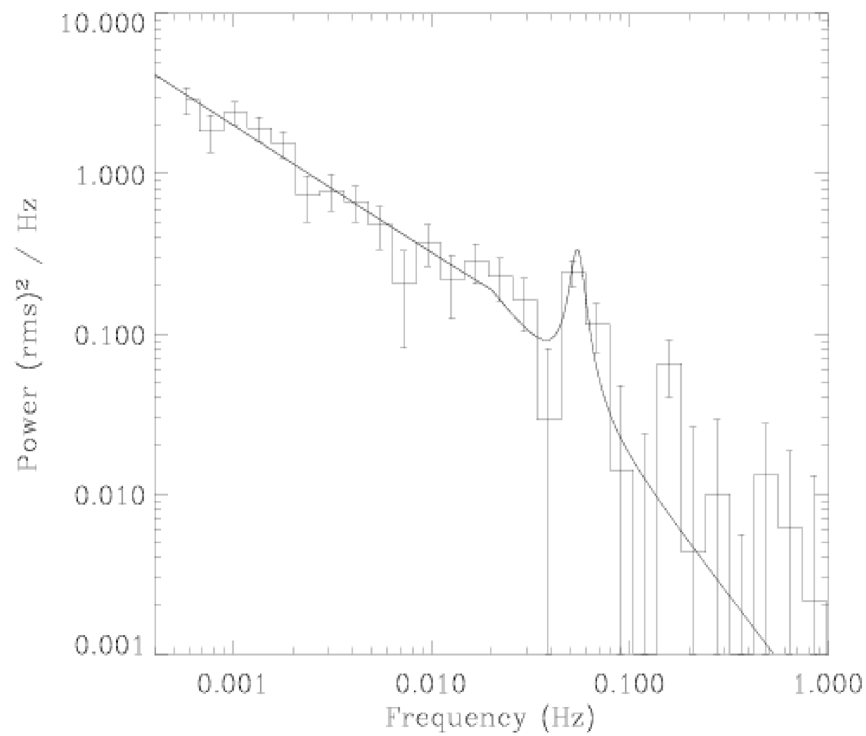




- Con-X will have sensitivity to PDS breaks and QPOs seen at low frequencies in the GBH systems for the brighter ULXs.
- Longer (200 ksec) pointings may be needed for fainter sources

Galaxy Populations: The Antennae





- Spatial resolution an issue, but should be able to do 6 -12 of the sources in the Antennae, obtain broad band PDS.

Final Comments

- Recent results are suggestive of IMBHs, but not yet conclusive. They do, however, establish the promise of more extensive and powerful studies.
- Longer XMM observations of the brightest ULXs might yield additional detections of QPOs, perhaps PDS's with breaks.
- We need better studies of the longterm (synoptic) behavior, ie. outburst properties, better coverage of state (spectral and timing) changes.
- Combination of large area, good angular resolution needed. Con-X should be able to make important contributions.
- If masses in 100s M_{sun} range, then HFQPOs at 10's of Hz, might be detectable.
- High spectral resolution capabilities (Astro-E2, Con-X), might yield some radial velocity information if velocities (ie. Masses) are high enough.

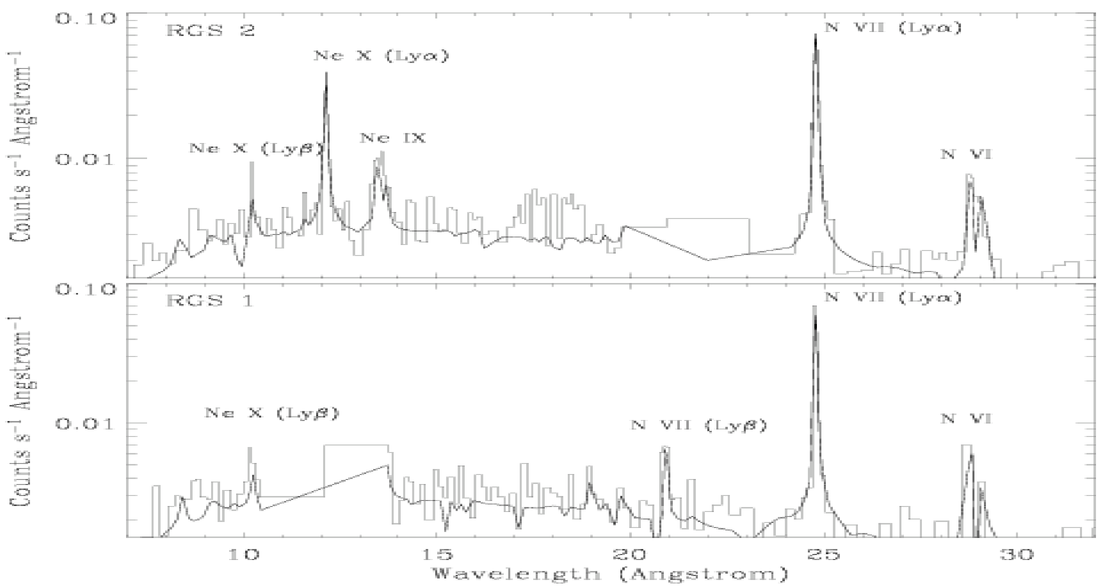
Con-X Science Objectives: Stellar Endpoints

- White Dwarfs: CV's, spectroscopy, recent AM CVn high resolution spectra, GP Com, ES Cet.

Could measure gravitational redshift from white dwarf surface, in several AM CVn's and magnetic CVs.

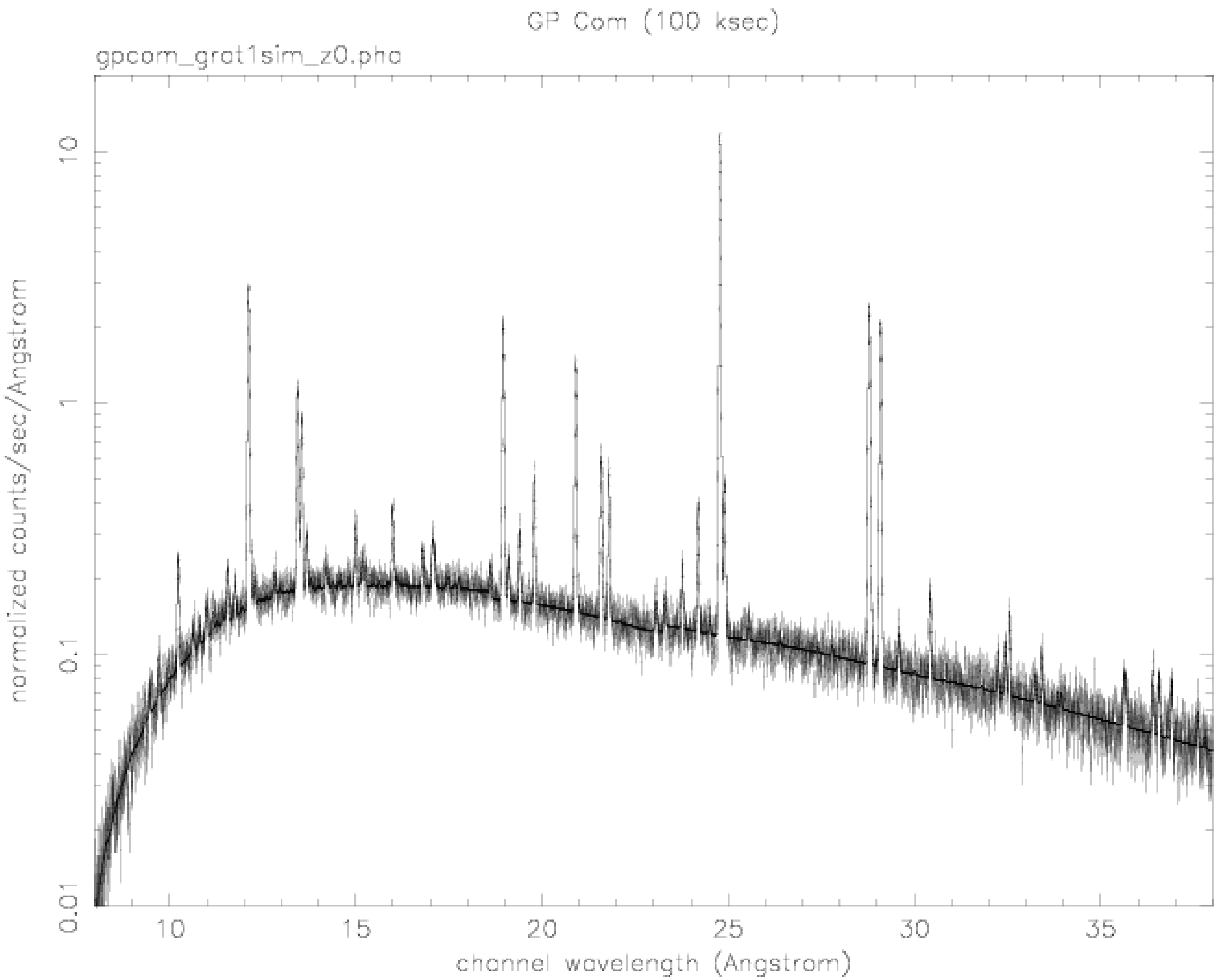
Probe boundary layers in detail, composition, plasma probes using helium-like triplets.

Perhaps obtain radial velocity information.

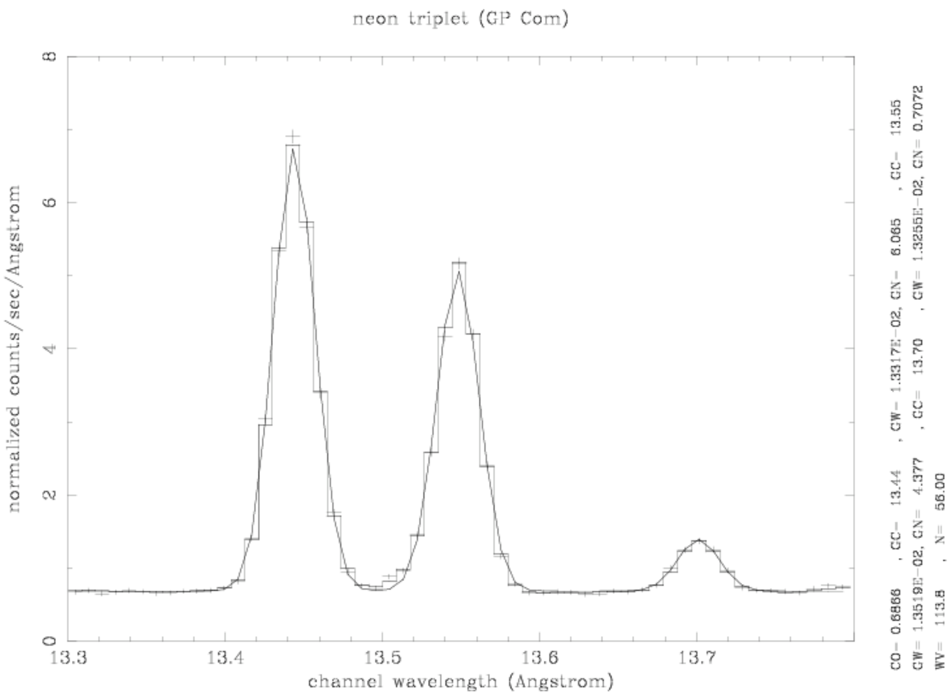


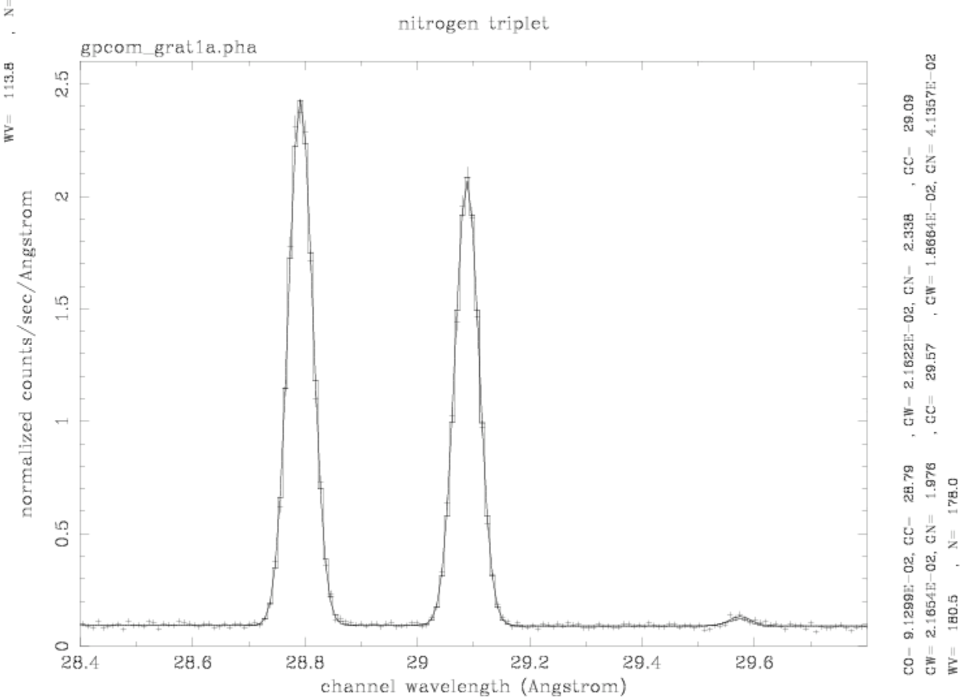
- Recent XMM/RGS spectrum of GP Com.
- Narrow lines of N and Ne detected, including He-like triplets.

White Dwarf Binaries: GP Com

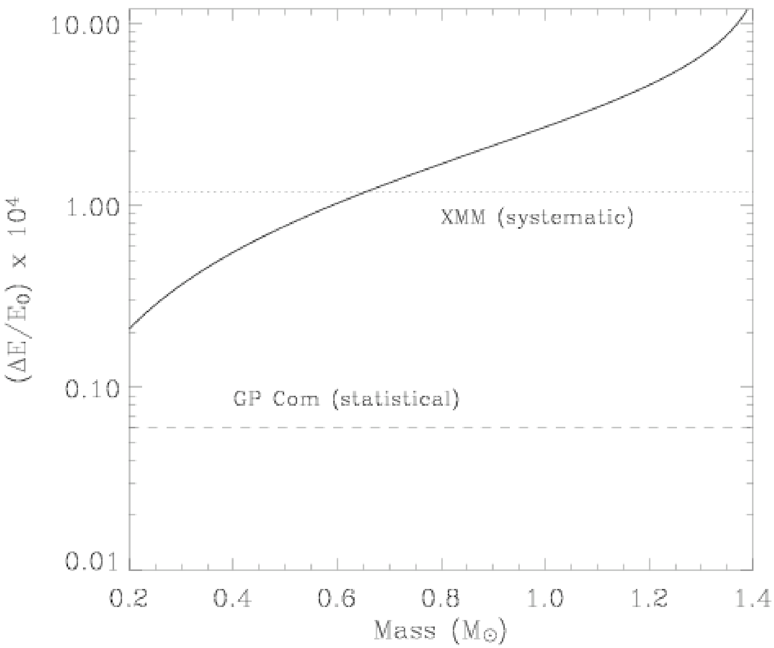


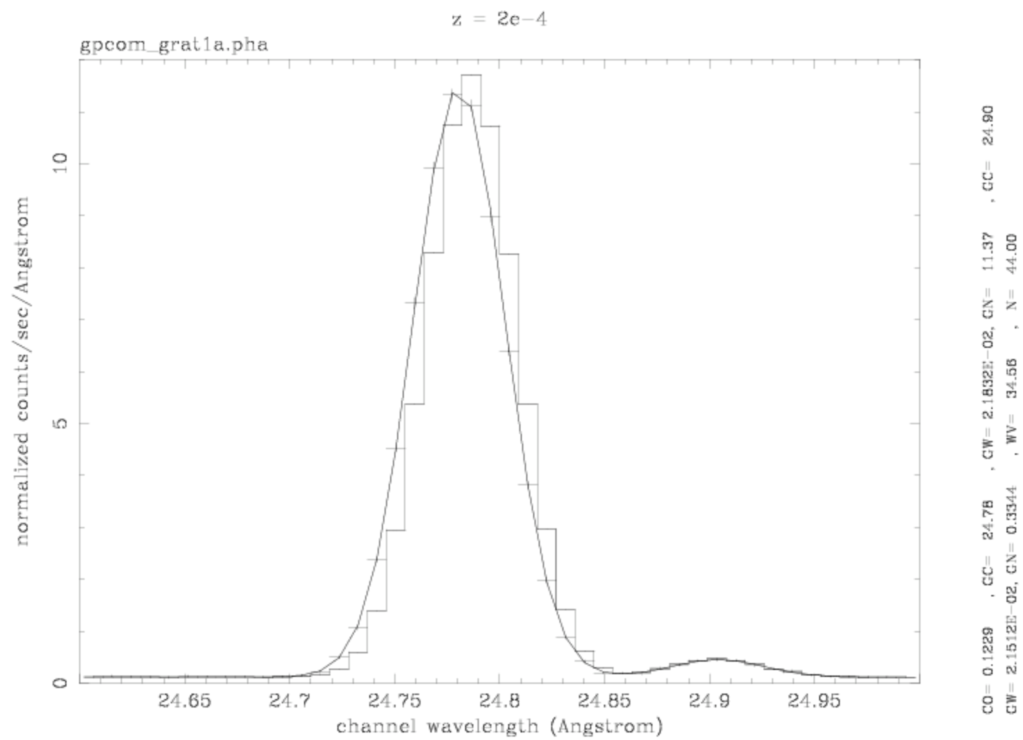
White Dwarf Binaries: GP Com



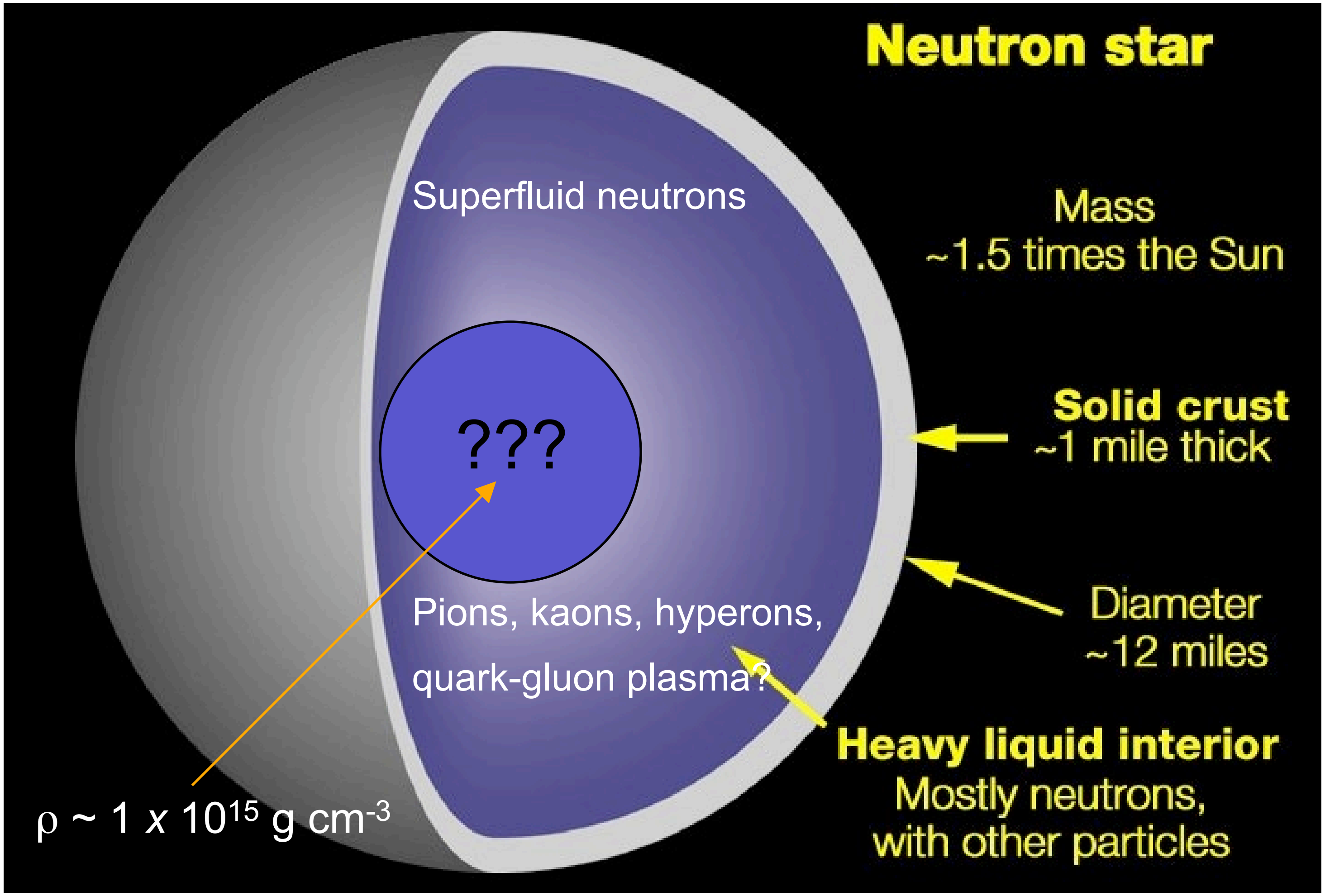


White Dwarf Binaries: GP Com



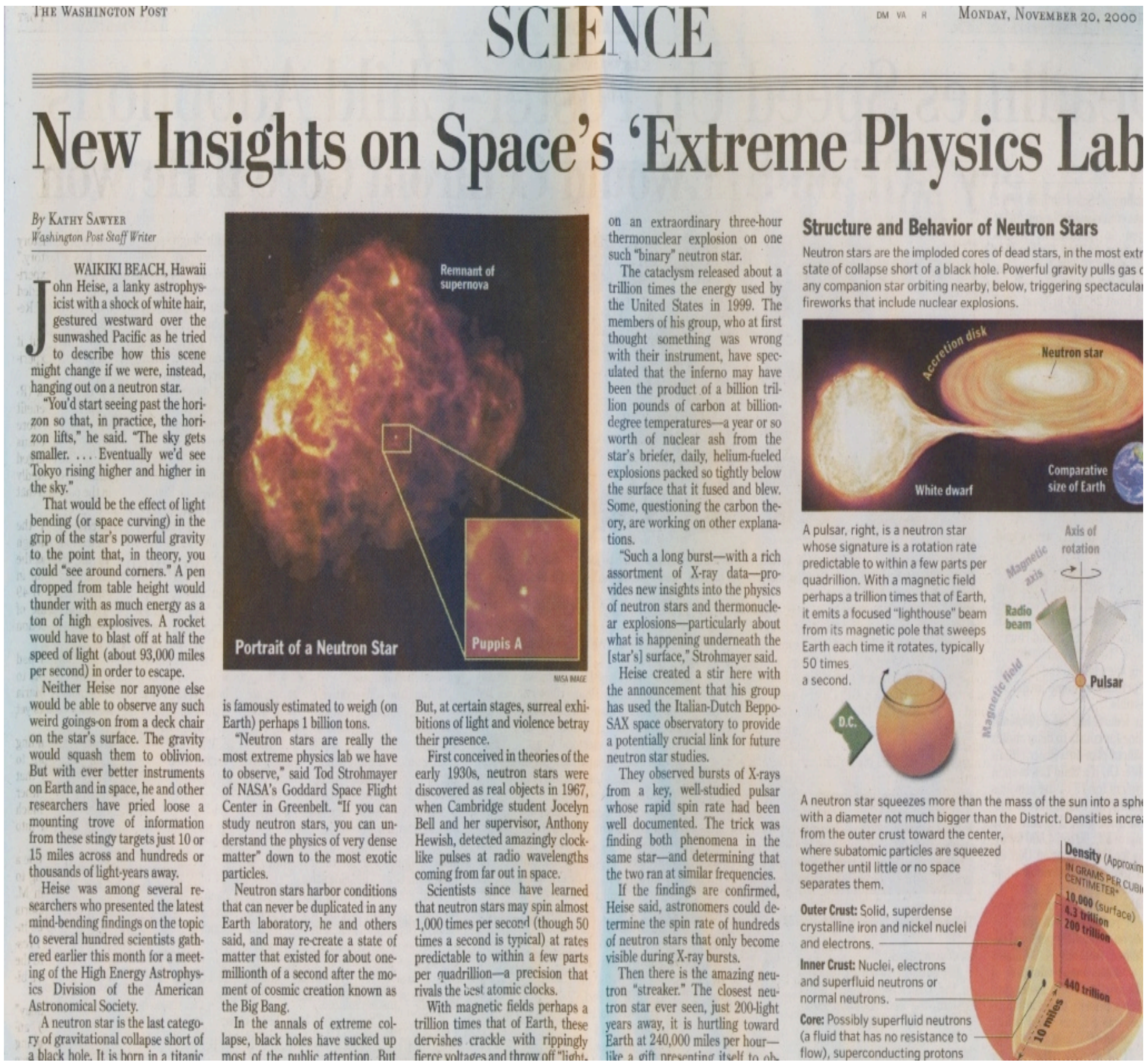


Inside Neutron Stars



- The physical constituents of neutron star interiors remain a mystery after 35 years. Constellation-X may finally provide the answers.

Compact Stellar Remnants
Nature's Extreme Physics Labs



THE WASHINGTON POST — SCIENCE — DM VA R — MONDAY, NOVEMBER 20, 2000

New Insights on Space's 'Extreme Physics Lab

By KATHY SAWYER
Washington Post Staff Writer

WAIKIKI BEACH, Hawaii

John Heise, a lanky astrophysicist with a shock of white hair, gestured westward over the sunwashed Pacific as he tried to describe how this scene might change if we were, instead, hanging out on a neutron star.

"You'd start seeing past the horizon so that, in practice, the horizon lifts," he said. "The sky gets smaller. . . . Eventually we'd see Tokyo rising higher and higher in the sky."

That would be the effect of light bending (or space curving) in the grip of the star's powerful gravity to the point that, in theory, you could "see around corners." A pen dropped from table height would thunder with as much energy as a ton of high explosives. A rocket would have to blast off at half the speed of light (about 93,000 miles per second) in order to escape.

Neither Heise nor anyone else would be able to observe any such weird goings-on from a deck chair on the star's surface. The gravity would squash them to oblivion. But with ever better instruments on Earth and in space, he and other researchers have pried loose a mounting trove of information from these stingy targets just 10 or 15 miles across and hundreds or thousands of light-years away.

Heise was among several researchers who presented the latest mind-bending findings on the topic to several hundred scientists gathered earlier this month for a meeting of the High Energy Astrophysics Division of the American Astronomical Society.

A neutron star is the last category of gravitational collapse short of a black hole. It is born in a titanic

Remnant of supernova

Portrait of a Neutron Star

Puppis A

NASA IMAGE

is famously estimated to weigh (on Earth) perhaps 1 billion tons.

"Neutron stars are really the most extreme physics lab we have to observe," said Tod Strohmayer of NASA's Goddard Space Flight Center in Greenbelt. "If you can study neutron stars, you can understand the physics of very dense matter" down to the most exotic particles.

Neutron stars harbor conditions that can never be duplicated in any Earth laboratory, he and others said, and may re-create a state of matter that existed for about one-millionth of a second after the moment of cosmic creation known as the Big Bang.

In the annals of extreme collapse, black holes have sucked up most of the public attention. But

But, at certain stages, surreal exhibitions of light and violence betray their presence.

First conceived in theories of the early 1930s, neutron stars were discovered as real objects in 1967, when Cambridge student Jocelyn Bell and her supervisor, Anthony Hewish, detected amazingly clock-like pulses at radio wavelengths coming from far out in space.

Scientists since have learned that neutron stars may spin almost 1,000 times per second (though 50 times a second is typical) at rates predictable to within a few parts per quadrillion—a precision that rivals the best atomic clocks.

With magnetic fields perhaps a trillion times that of Earth, these dervishes crackle with rippingly fierce voltages and throw off "light-

on an extraordinary three-hour thermonuclear explosion on one such "binary" neutron star.

The cataclysm released about a trillion times the energy used by the United States in 1999. The members of his group, who at first thought something was wrong with their instrument, have speculated that the inferno may have been the product of a billion trillion pounds of carbon at billion-degree temperatures—a year or so worth of nuclear ash from the star's briefer, daily, helium-fueled explosions packed so tightly below the surface that it fused and blew. Some, questioning the carbon theory, are working on other explanations.

"Such a long burst—with a rich assortment of X-ray data—provides new insights into the physics of neutron stars and thermonuclear explosions—particularly about what is happening underneath the [star's] surface," Strohmayer said.

Heise created a stir here with the announcement that his group has used the Italian-Dutch BeppoSAX space observatory to provide a potentially crucial link for future neutron star studies.

They observed bursts of X-rays from a key, well-studied pulsar whose rapid spin rate had been well documented. The trick was finding both phenomena in the same star—and determining that the two ran at similar frequencies.

If the findings are confirmed, Heise said, astronomers could determine the spin rate of hundreds of neutron stars that only become visible during X-ray bursts.

Then there is the amazing neutron "streaker." The closest neutron star ever seen, just 200-light years away, it is hurtling toward Earth at 240,000 miles per hour—like a gift presenting itself to ob-

Structure and Behavior of Neutron Stars

Neutron stars are the imploded cores of dead stars, in the most extr state of collapse short of a black hole. Powerful gravity pulls gas any companion star orbiting nearby, below, triggering spectacular fireworks that include nuclear explosions.

Accretion disk
Neutron star
White dwarf
Comparative size of Earth

A pulsar, right, is a neutron star whose signature is a rotation rate predictable to within a few parts per quadrillion. With a magnetic field perhaps a trillion times that of Earth, it emits a focused "lighthouse" beam from its magnetic pole that sweeps Earth each time it rotates, typically 50 times a second.

Axis of rotation
Magnetic axis
Radio beam
Pulsar
Magnetic field
D.C.

A neutron star squeezes more than the mass of the sun into a sph with a diameter not much bigger than the District. Densities increa from the outer crust toward the center, where subatomic particles are squeezed together until little or no space separates them.

Outer Crust: Solid, superdense crystalline iron and nickel nuclei and electrons.

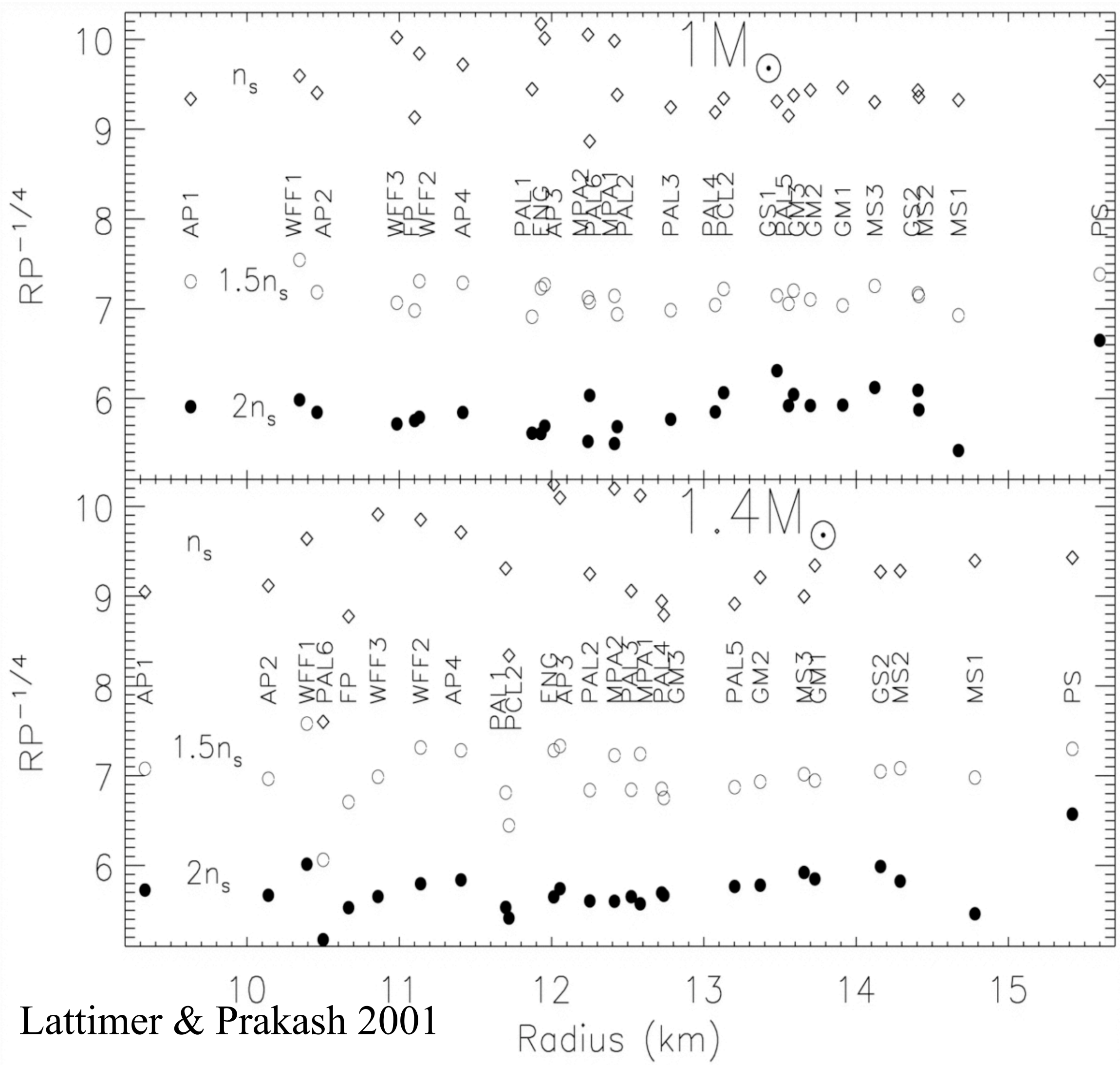
Inner Crust: Nuclei, electrons and superfluid neutrons or normal neutrons.

Core: Possibly superfluid neutrons (a fluid that has no resistance to flow), superconducting protons

Density (Approxim IN GRAMS PER CUBI CENTIMETER
10,000 (surface)
4.3 trillion
200 trillion
440 trillion
10 miles

- Neutron stars, ~1.5 Solar masses compressed inside a sphere ~20 km in diameter.
- Highest density matter "observable" in universe.
- Highest magnetic field strengths "observable" in the universe.
- Black holes, strongest gravitational fields accessible to study.
- General Relativity (GR) *required* to describe structure.

Fundamental Physics: The Neutron Star Equation of State (EOS)



Lattimer & Prakash 2001

- Radius is weakly dependent on Mass for many EOSs.
- Precise radius measurements alone would strongly constrain the EOS.
- Radius is prop. to $P^{1/4}$ at nuclear saturation density. Directly related to symmetry energy of nuclear interaction (isospin dependence).

Neutron Star Mass and Radius Measurements

- Some neutron star masses are known very accurately (binary pulsars), but radii are extremely difficult to measure. Essentially no simultaneous M and R measurements.
- A number of different methods can be used; timing, continuum spectroscopy, cooling curves, but none at present sufficiently accurate.
- Most powerful method (in theory) is high resolution X-ray spectroscopy (Constellation-X).

A spectral line emitted at energy E_0 at the neutron star surface is redshifted by GR to energy $E_{obs} = E_0 (1 - 2GM/c^2R)^{1/2}$. Depends on the ratio M/R.

Widths of lines depend on surface gravity M/R^2 (Stark effect broadening), and rotational velocity (depends on R for known spin frequency).

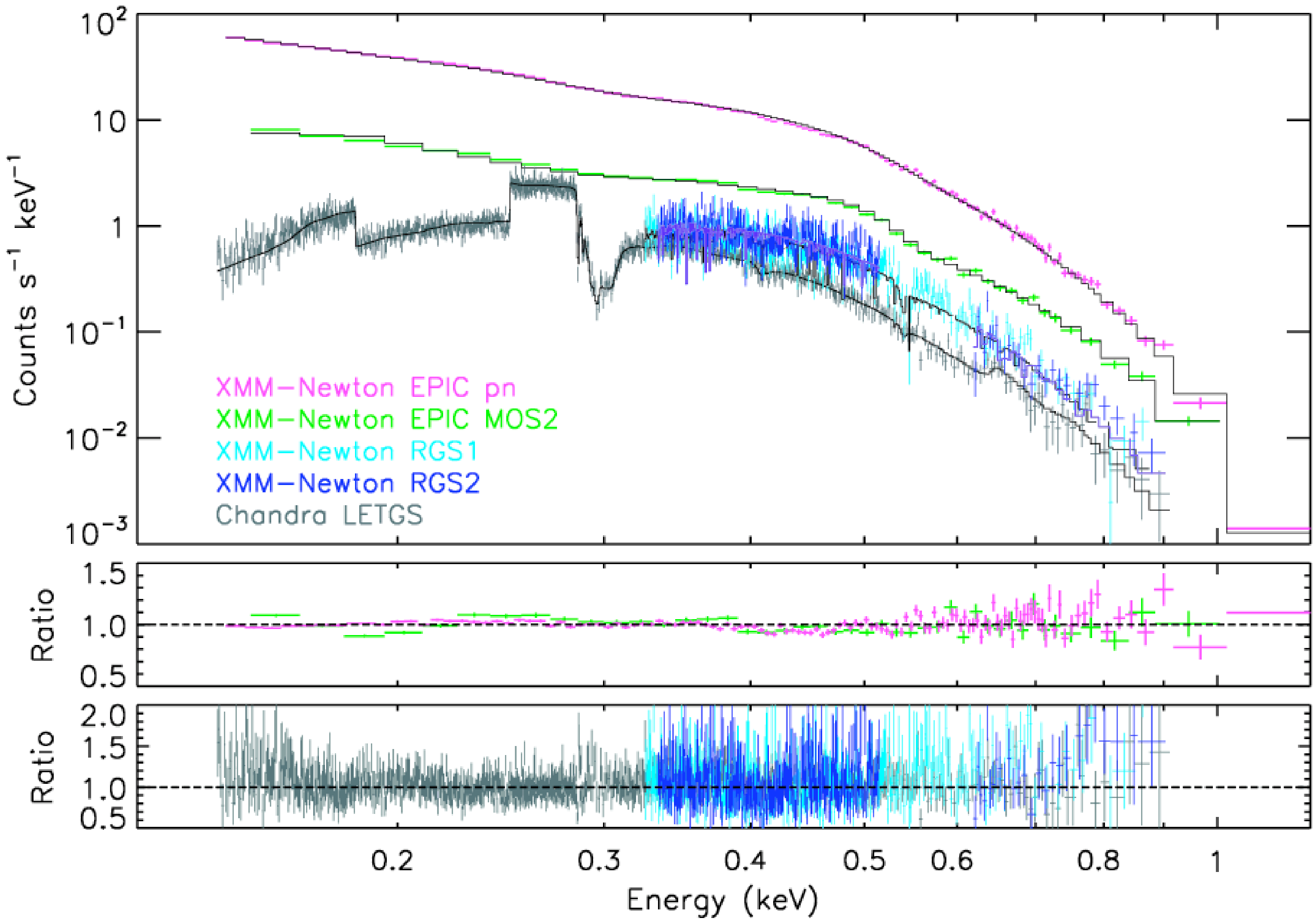
Measurement, and correct physical interpretation, of both line energies and widths will determine both M and R.

Neutron Star Mass and Radius Measurements, Cont'

Other methods which future missions will be able to exploit:

- Burst oscillation pulse profile fitting. Pulse amplitudes contain information on compactness, M/R. Pulse shapes (harmonic content) contain information on R.
- Line profiles from rapidly rotating neutron stars (burst oscillation sources). Observed redshifts give M/R. Line widths constrain R if spin frequency and system inclination known.
- Continuum spectroscopy. Broad-band spectral fits with 'correct' model atmosphere, constrain R (distance required, globular cluster sources promising).
- Neutron star cooling. Surface temperatures for sources of known age constrain internal structure.

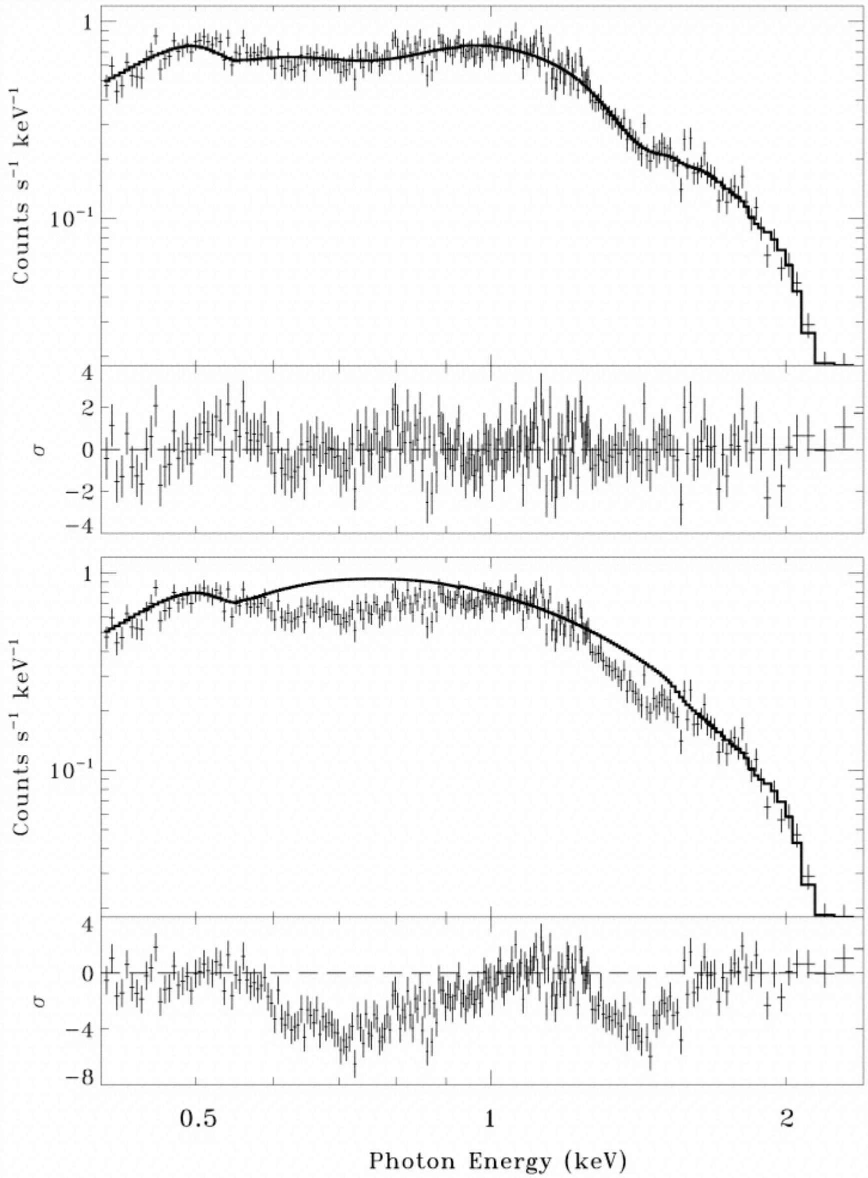
Line Searches from Isolated Neutron Star RX J1856.5-3754

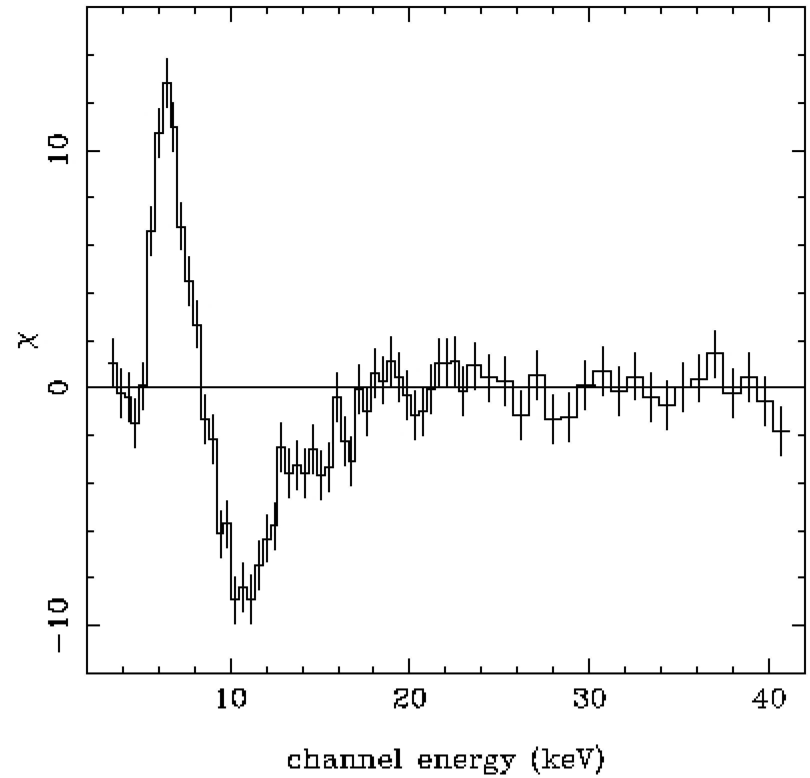


Burwitz et al. (2003)

- No line features detected with Chandra and XMM

X-ray Spectroscopy of Neutron Stars: Line Detections

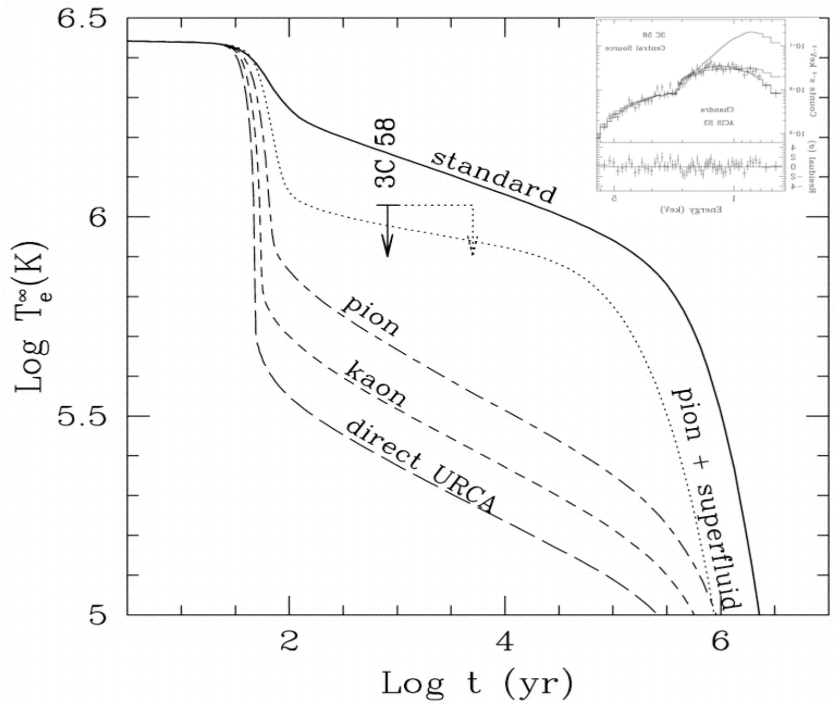




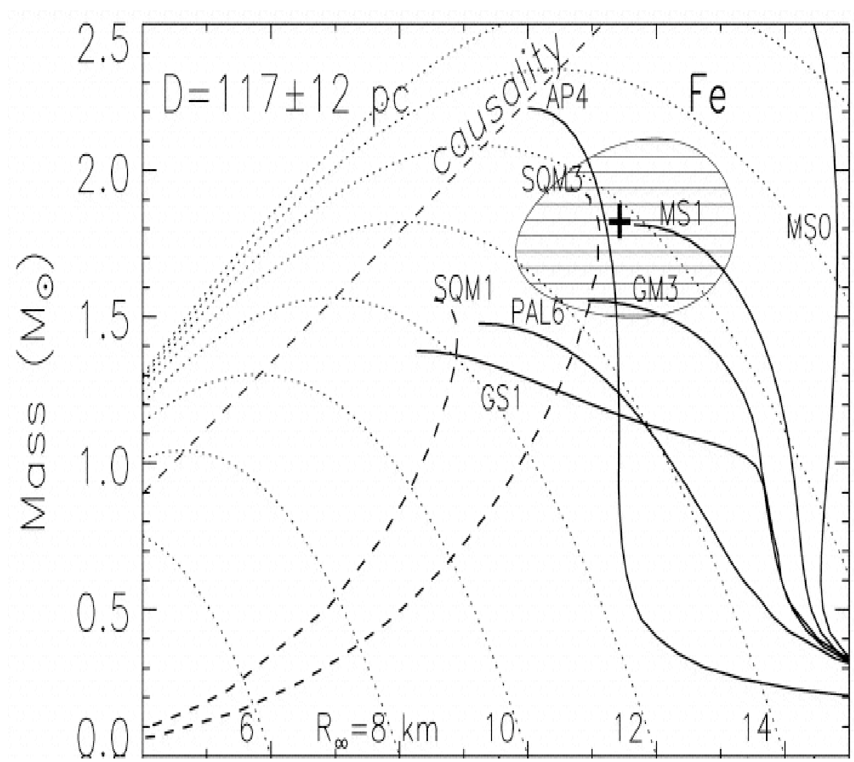
Spectral line and edge from RXTE observations of thermal emission from accreting neutron star (4U 1820-30; Strohmayer & Brown 2002)

Chandra (ACIS) detection of absorption lines in a SNR neutron star (1E 1207.4-5209; Sanwal et al. 2002)

Neutron Star Continuum Spectroscopy and Cooling

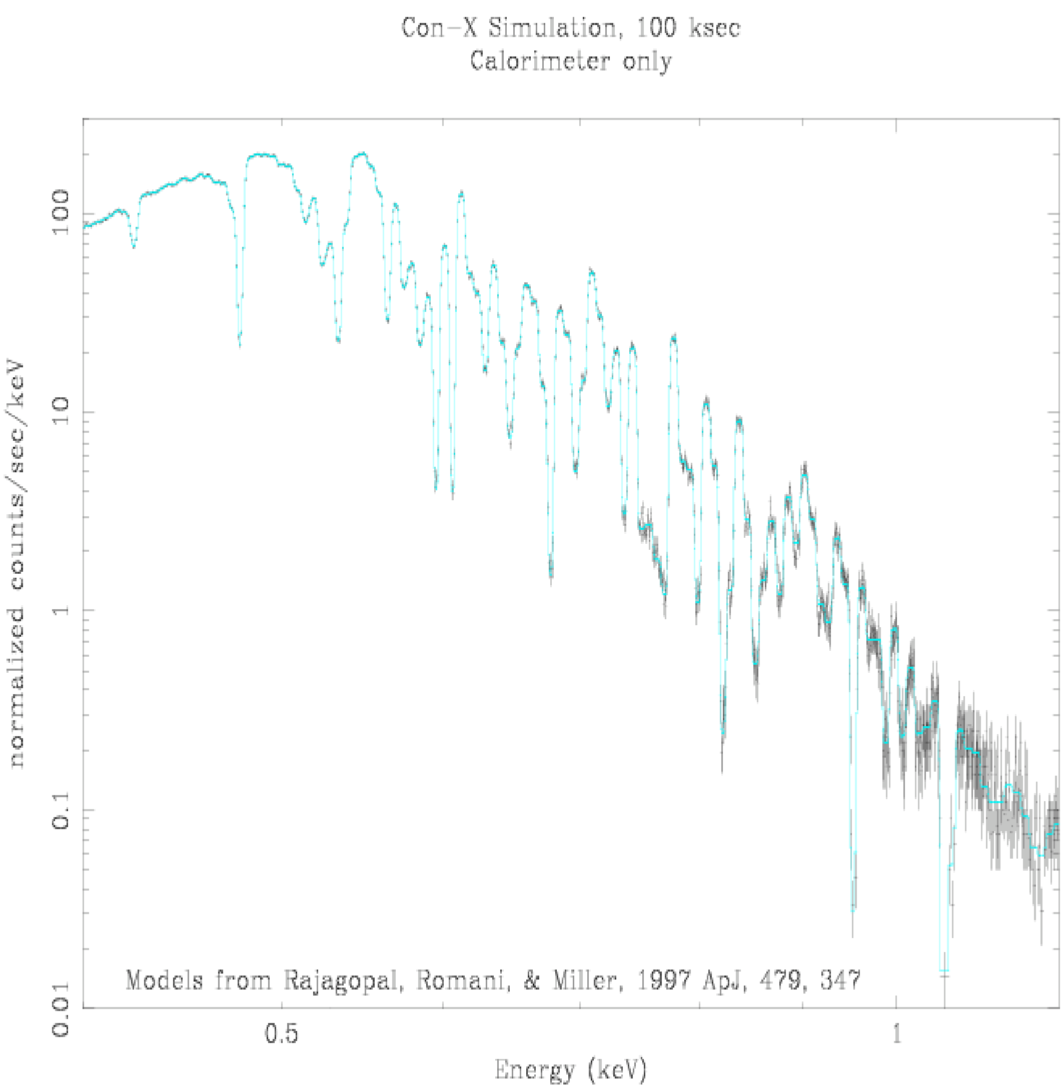


- Chandra observations of nearby, isolated NS (RX J1856.35-3754) combined with distance estimate (from HST parallax) give radius estimates consistent with normal NS (Walter et al. 2002)



- Slane et al. (2002) used Chandra spectra to determine upper limit to T_{eff} of neutron star in SNR 3C 58.
- Age known from historical observations of remnant (A.D. 1181).
- Relatively low T_{eff} suggestive of non-standard cooling.

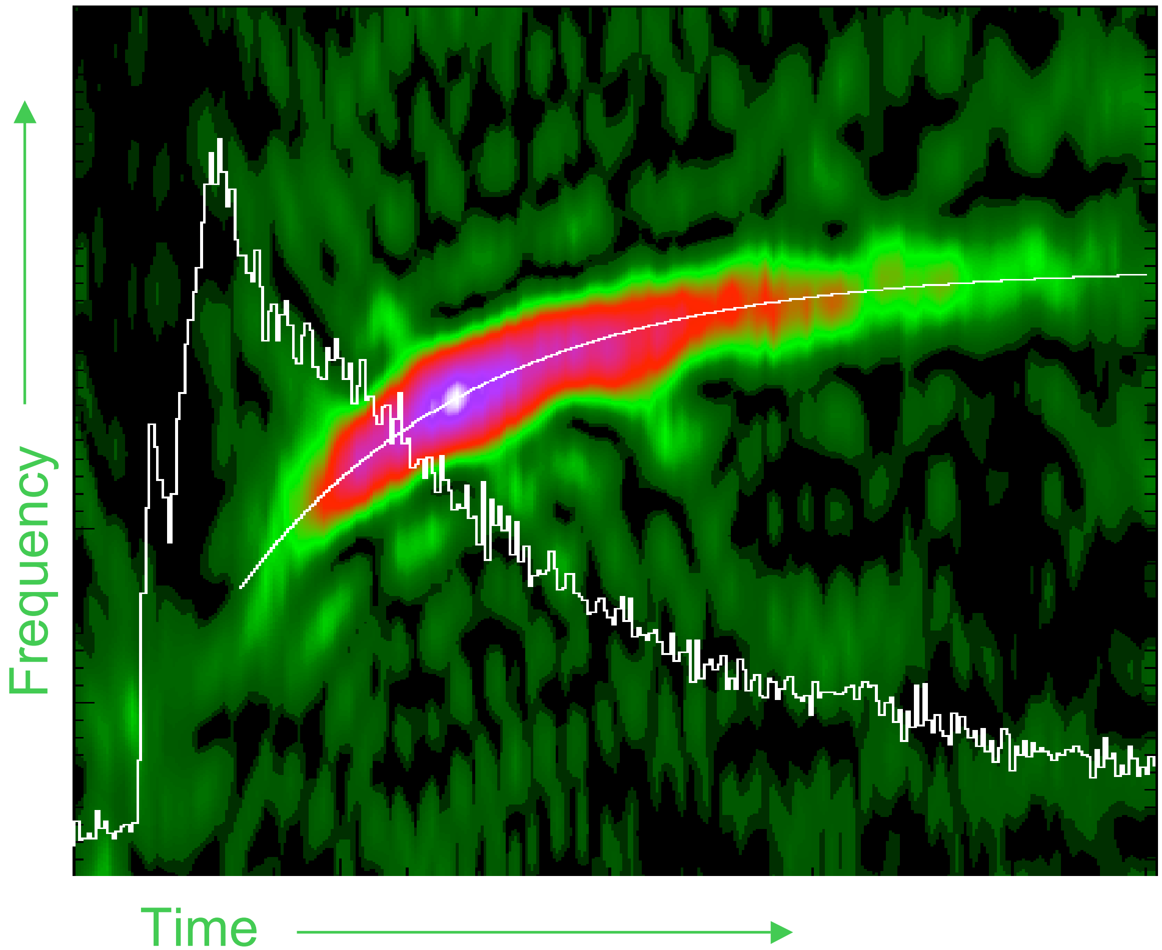
The Future with Constellation-X



- Line Searches with Con-X will be much more sensitive (factor of 10-100). Due to larger area.
- Higher spectral resolution across broader bandpass; more phase-space within which to discover features.
- Phase resolved - high resolution spectra of rapidly rotating neutron stars will be possible. Could lead to R measurements from Doppler effect caused by rotational velocity.
- Relevant objects are faint. With Constellation, more sources, and new classes (NS transients in quiessence), can be searched for lines

Burst Oscillations: Measuring the Spin Rates of Neutron Stars

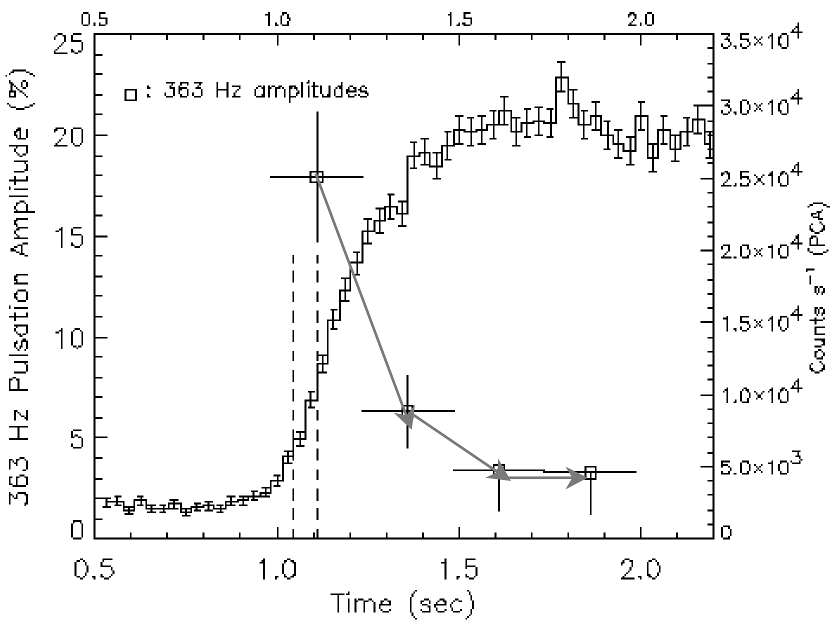
Strohmayer & Markwardt (1999)

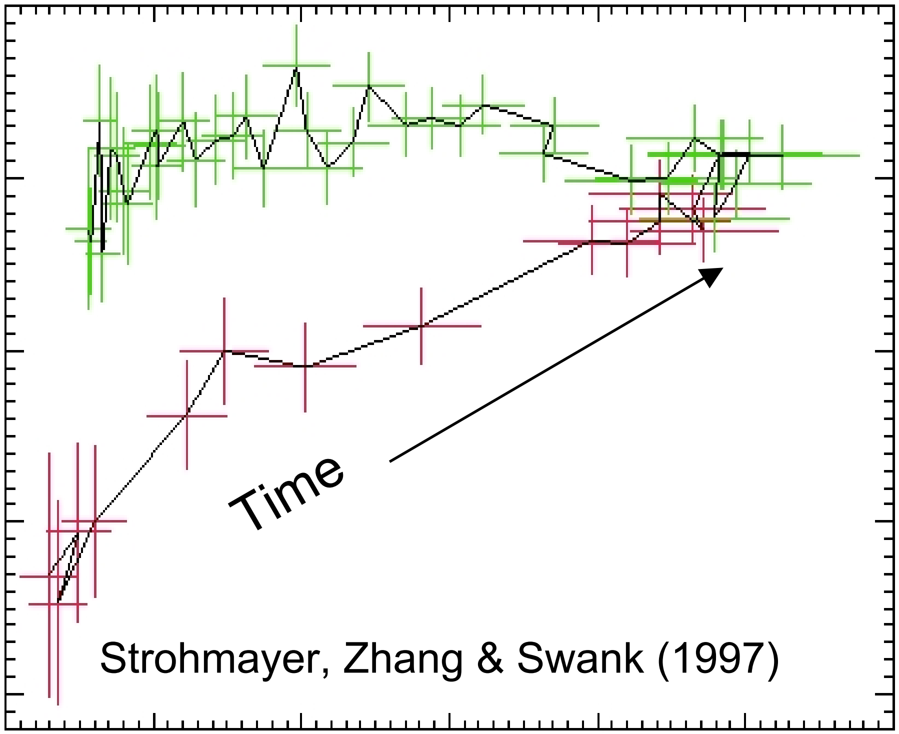


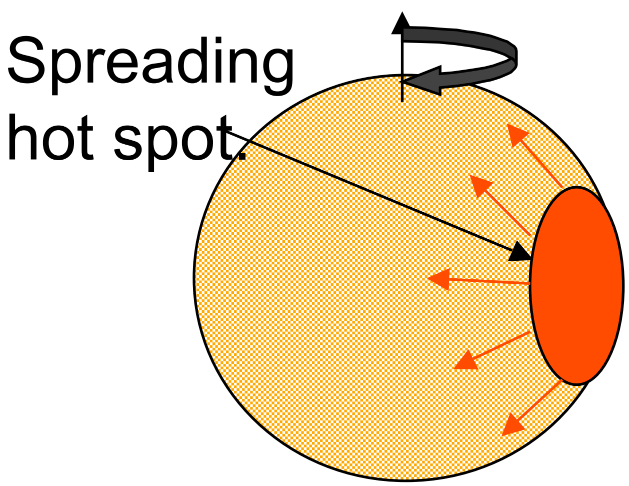
Dynamic power spectrum of a burst from 4U 1702-429

- 300 - 600 Hz X-ray brightness oscillations seen during thermonuclear bursts.
- Observed frequency is the neutron star spin frequency.
- Detected in 12 low mass X-ray binaries to date.
- Rotational modulation of an asymmetric emission pattern on NS.

Timing and Spectral Evidence for Rotational Modulation

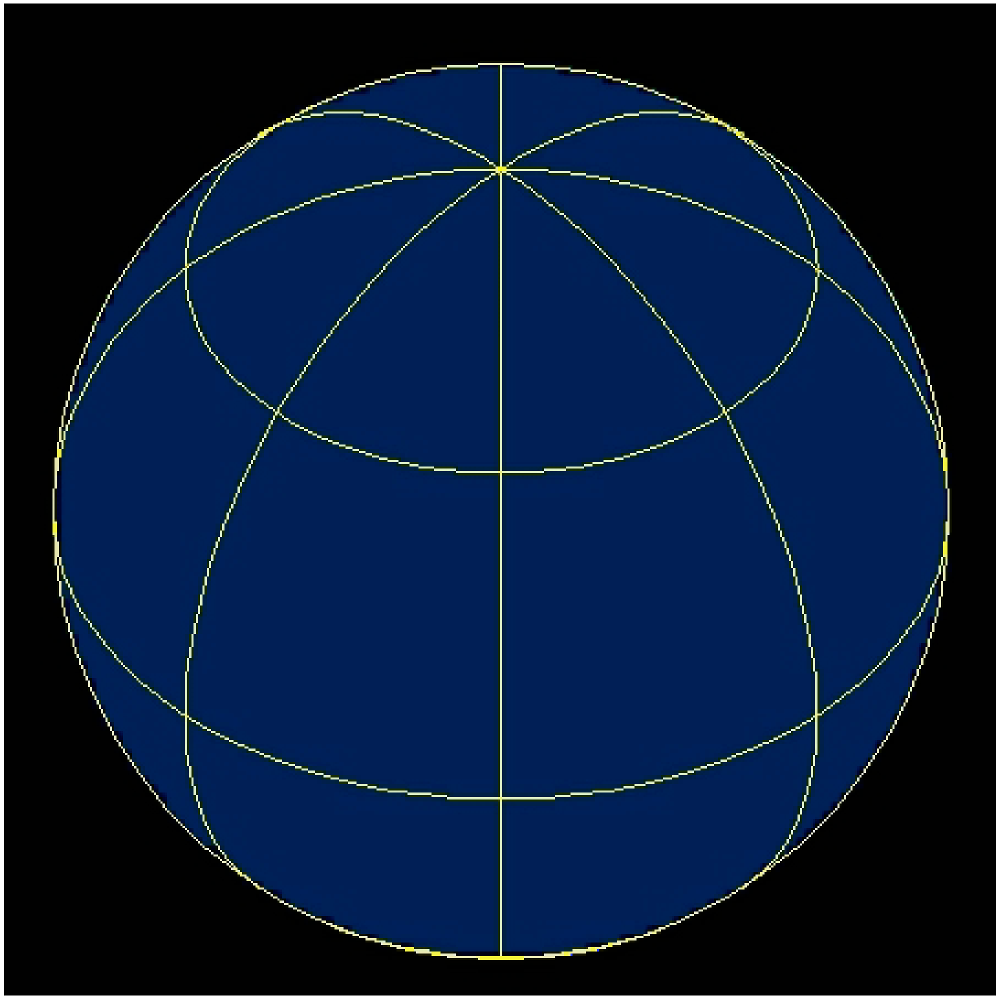






- Oscillations caused by hot spot on rotating neutron star
- Modulation amplitude drops as spot grows.
- Spectra track increasing size of X-ray emitting area on star.

Burst Oscillations: Ignition and Spreading.

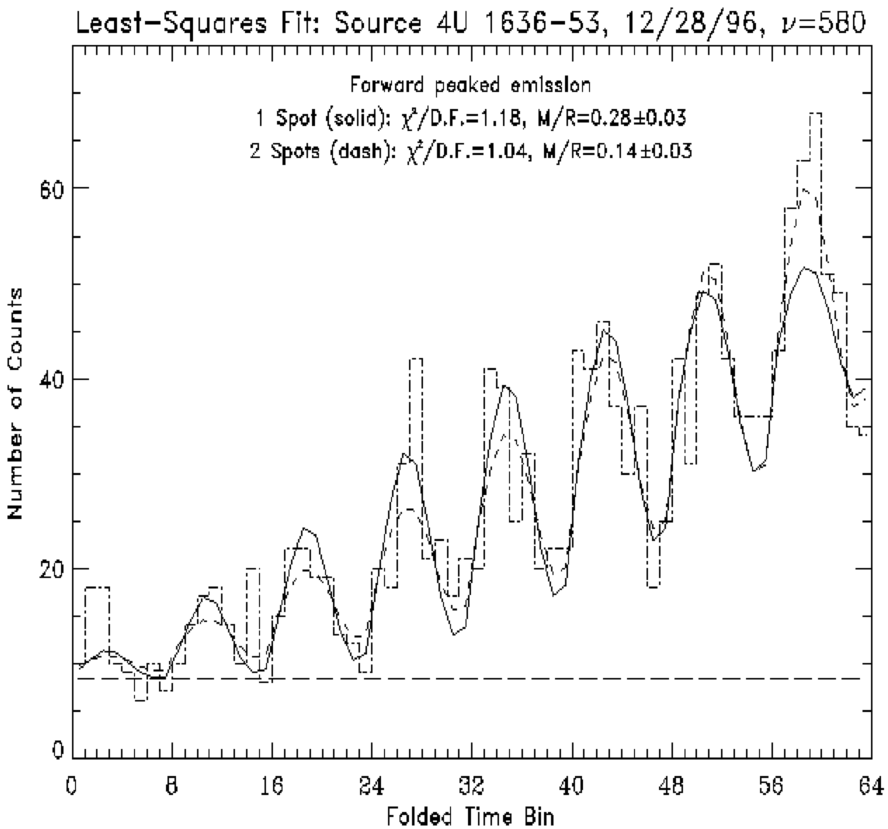


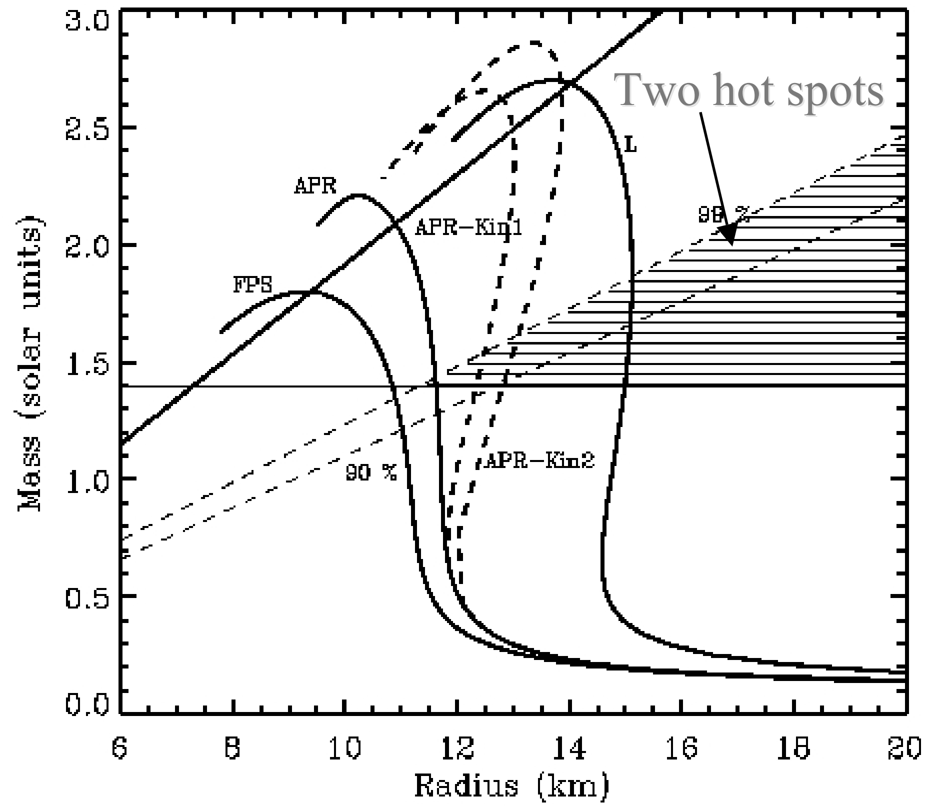
Credit: Anatoly Spitkovsky (2003)

- Combining spreading theory (Spitkovsky, Levin & Ushomirsky 2002), with burning calculations (Schatz, Bildsten, Cumming, Heger, Woosley…), can give detailed predictions for hot spot geometry and lightcurves.
- Comparison with precision measurements can probe various burning physics as well as the neutron star properties.

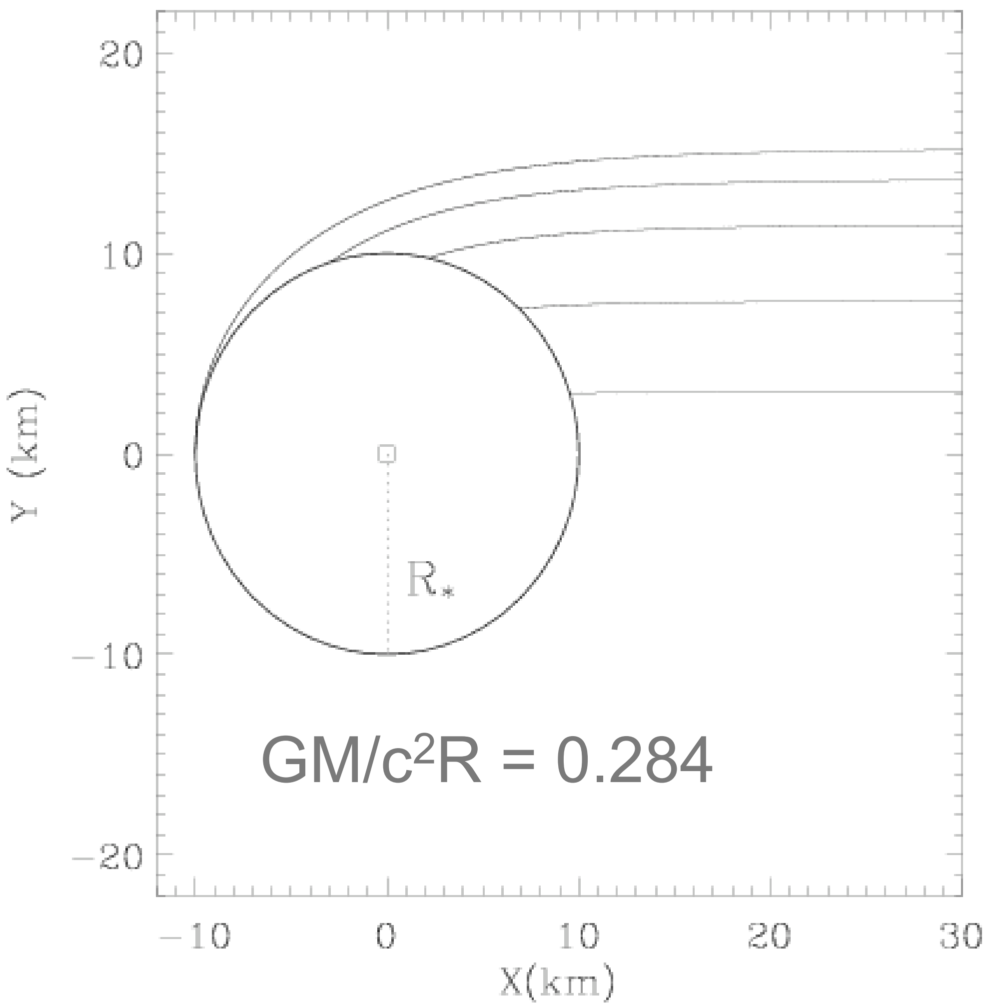
Burst Oscillations Probe the Structure of Neutron Stars

- Pulse strength and shape depends on M/R or ‘compactness’ because of light bending (a General Relativistic effect).
- Rotational velocity introduces aberration and Doppler boosting, can measure R if spin frequency known.
- More compact stars have weaker modulations.



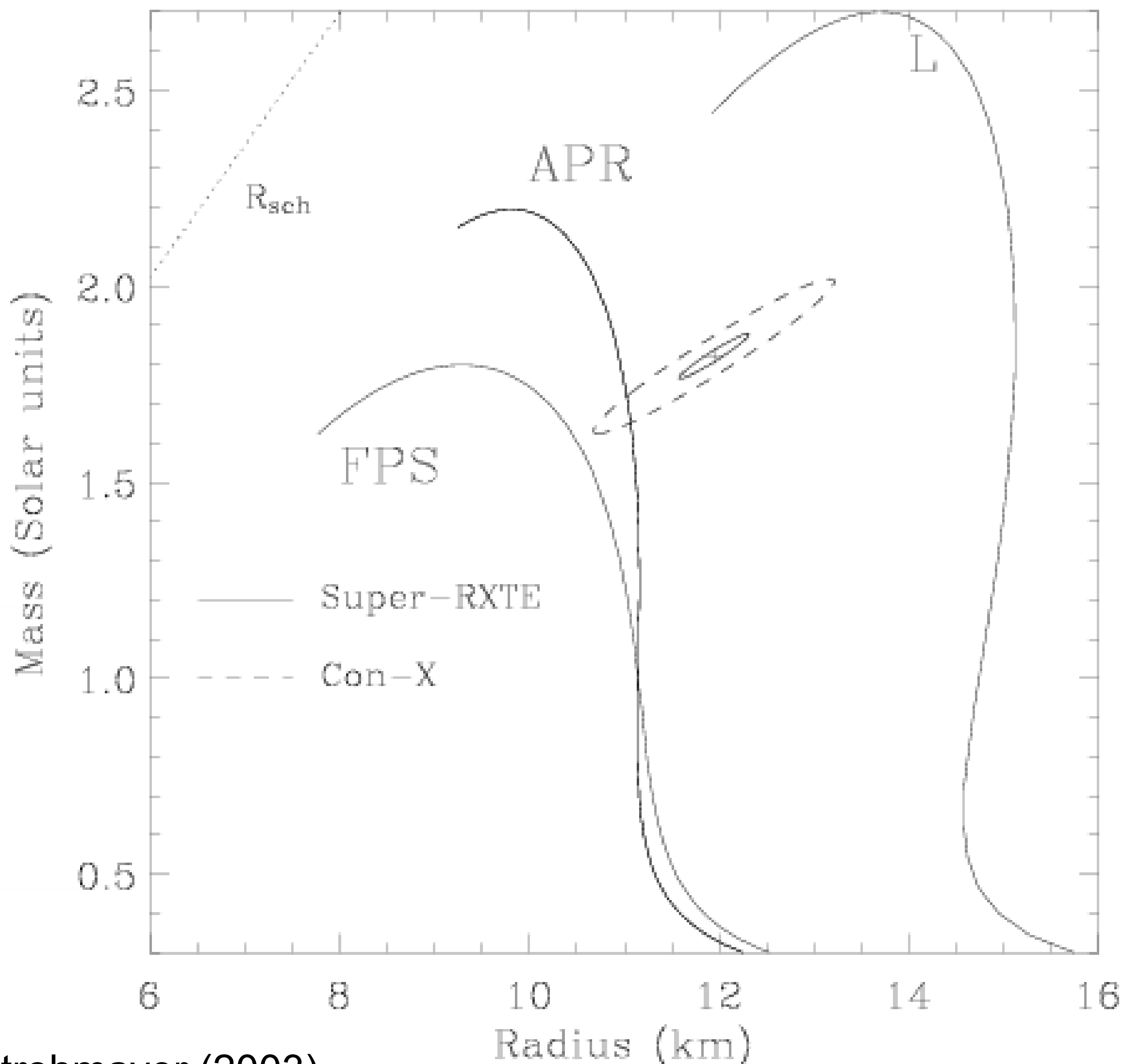


Rotational Modulation of Neutron Star Emission: The Model



- Gravitational Light Deflection: Schwarzschild metric.
- Gravitational redshift
- Rotational doppler shifts and aberration of the intensity.
- "Beaming" of intensity in NS rest frame.
- Arbitrary geometry of emission regions.
- Observed response using various detector response matrices.

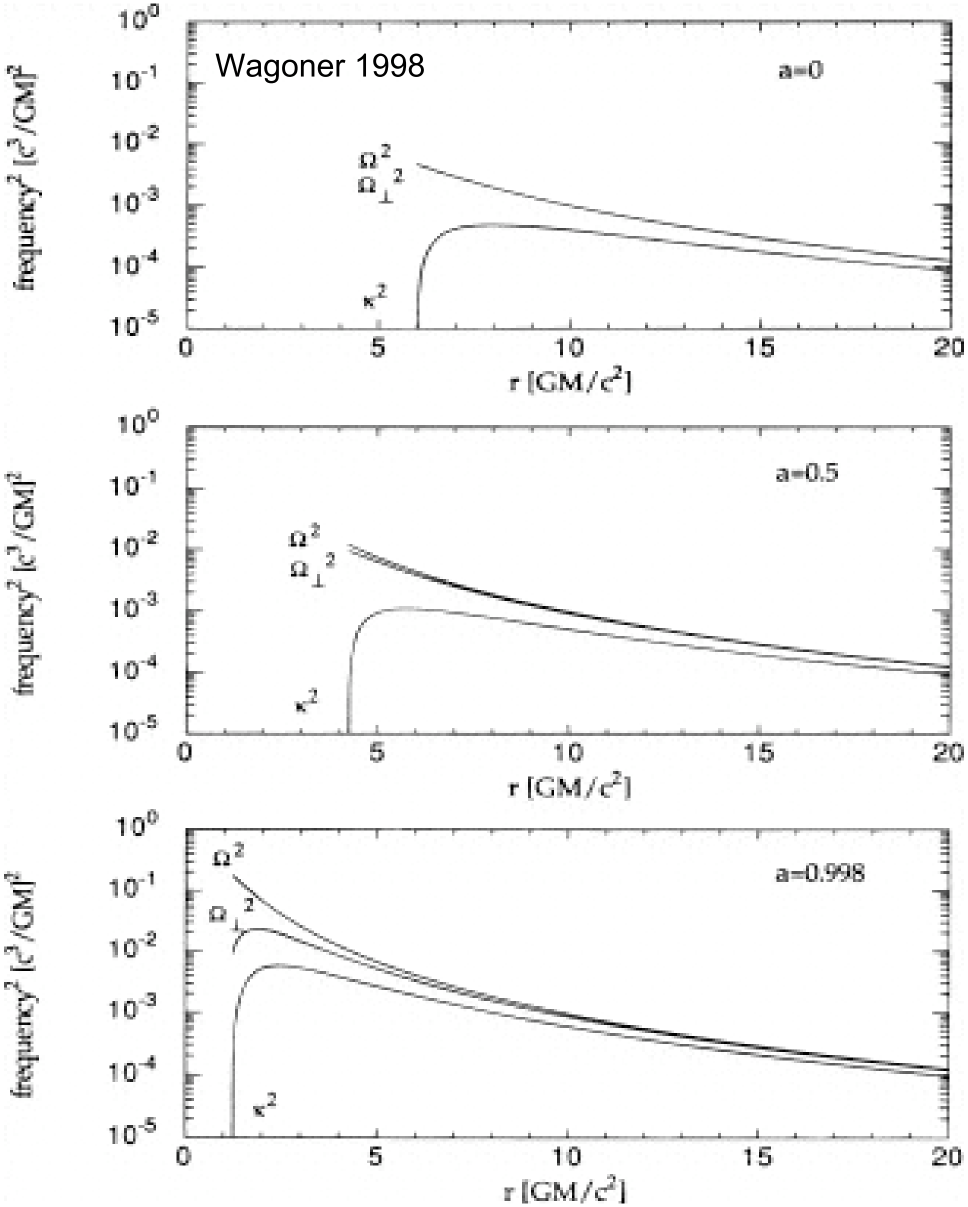
Burst Oscillations and M - R Constraints for Neutron Stars



Strohmayer (2003)

- Pulse shapes of burst oscillations encode information on the neutron star mass and radius.
- Modulation amplitude sensitive to compactness, M/R.
- Pulse sharpness (harmonic content) sensitive to surface velocity, and hence radius for known spin frequency.
- Geometry and evolution of the hot region can be a complicating factor.
- Statistical limits for future missions look promising.

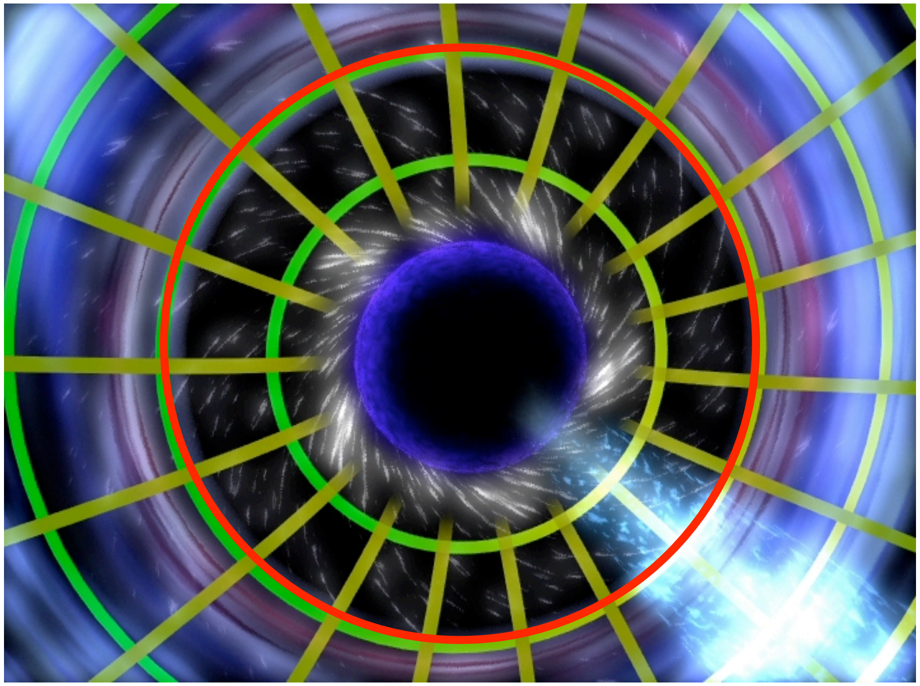
General Relativistic Frequencies in Black Hole Accretion Disks



- GR fundamentally changes orbit dynamics.
- Inner-most stable circular orbit (ISCO).
- 3 characteristic particle frequencies at a given radius.
- Leads to apsidal and gravito-magnetic precession.
- Mode trapping.

Constraining Black Hole Spin

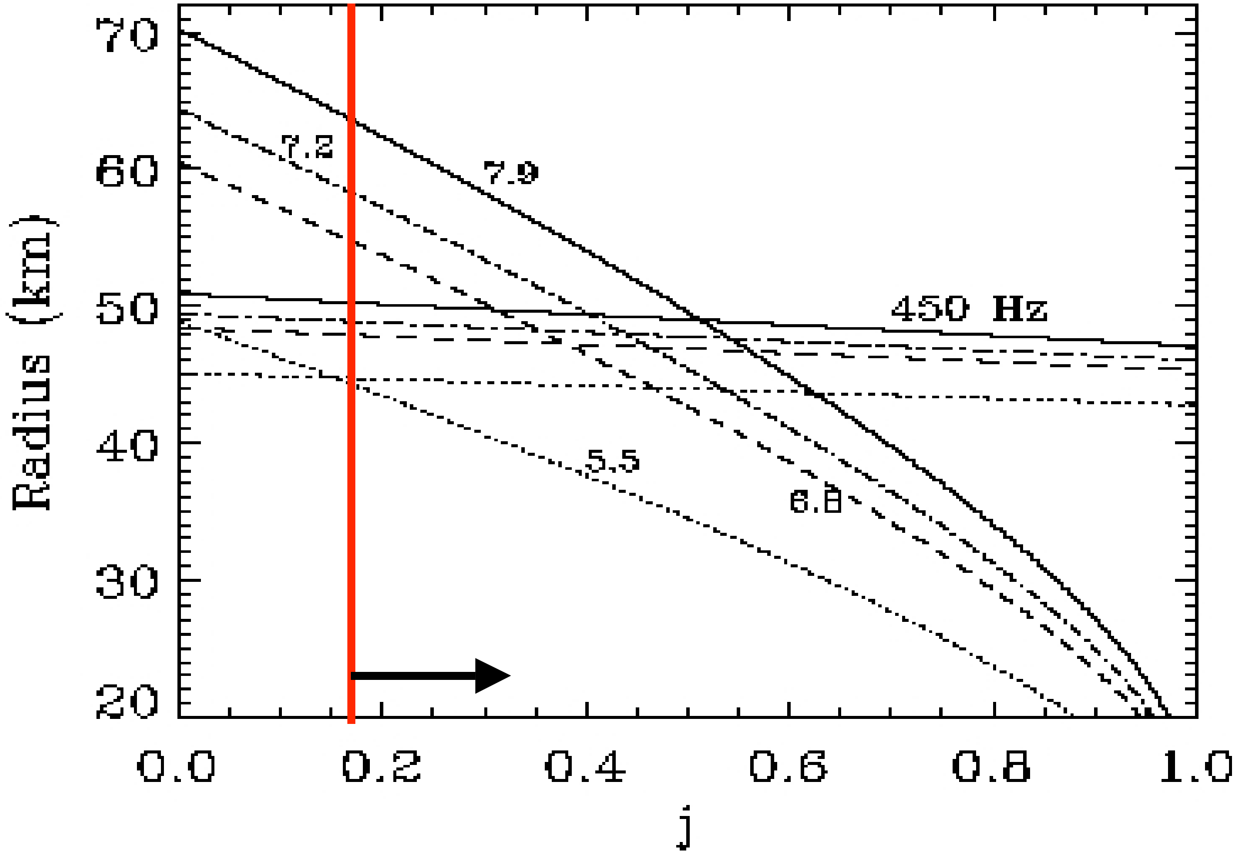
- Highest characteristic frequency at a given radius is the Keplerian (orbital) frequency.
- Stable circular orbits extend closer to spinning black hole.
- Closer orbits have higher orbital frequencies.

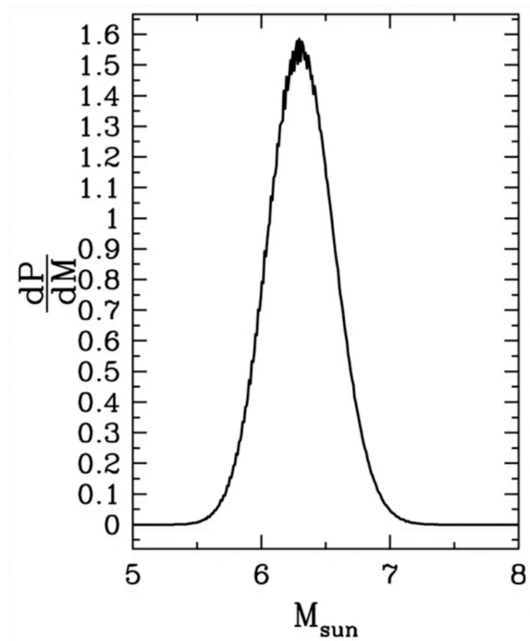


Schwarzschild (non-rotating)

Kerr (rotating)

Evidence for Black Hole Spin in GRO J1655-40





- Mass of GRO J1655-40 tightly constrained M = 6.3 ± 0.5 $M_{\odot}$ (Greene, Bailyn & Orosz 2001).
- 450 Hz QPO in GRO J1655-40 is too high for non-rotating hole.

Summary

- Constellation-X will have superb capabilities for line searches from neutron star surfaces.
- We are starting to see line features! Follow-up observations of recently discovered lines with Constellation-X will confirm them and provide the higher quality data for detailed study and firm identifications of the features.
- Deeper and broader line searches will be possible, from a wider class of sources.
- Measurement of gravitational redshifts could lead to a breakthrough in understanding of the neutron star Mass - Radius relation and thus fundamental physics (EOS of dense matter; nucleon interactions).
- Challenges: Atomic structure, line formation and radiative transfer in strong magnetic fields will likely be required to fully exploit science potential.

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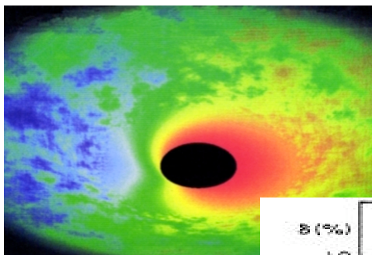
No Lines from Some Neutron Stars

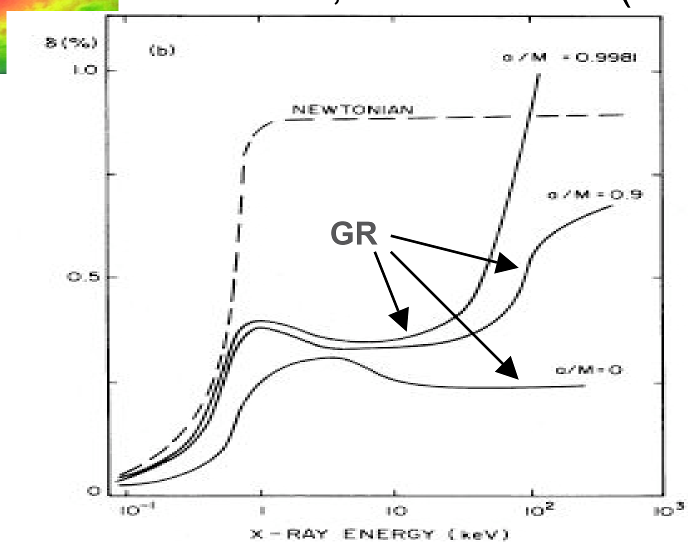
- Chandra and XMM have performed searches for lines in several other good candidate neutron stars (RX J1865-3754, Vela pulsar, 4U 0142+61). No line features have been found.
- Spectra consistent with thermal, H-dominated atmospheres. If metal content is low, then X-ray lines may be difficult to detect (need collecting area).
- Strong magnetic fields will need to be incorporated in line formation, atomic processes. Rapid spin can also broaden, and weaken line features.
- Neutron stars are observed in diverse circumstances, X-ray lines will likely be more easily observed in some classes than others. For example, B fields range from 10^{8-15} G.

X-ray Polarization: A New Probe of Strong Gravity

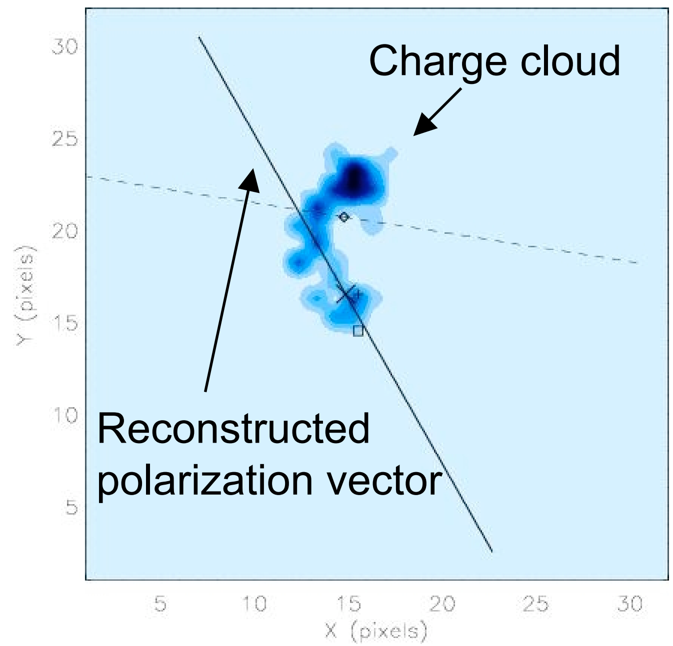
- Near a Black hole General Relativity can rotate the polarization vector of photons.
- Hotter regions closer to the black hole are more strongly affected.
- This leaves a characteristic signature in the polarization fraction versus photon energy, sensitive to black hole spin.



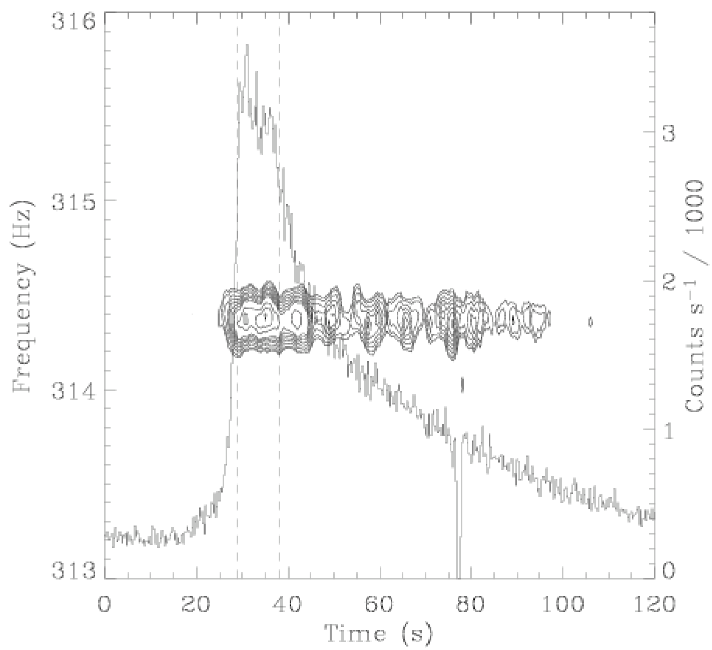
Connors, Stark & Piran (1980)

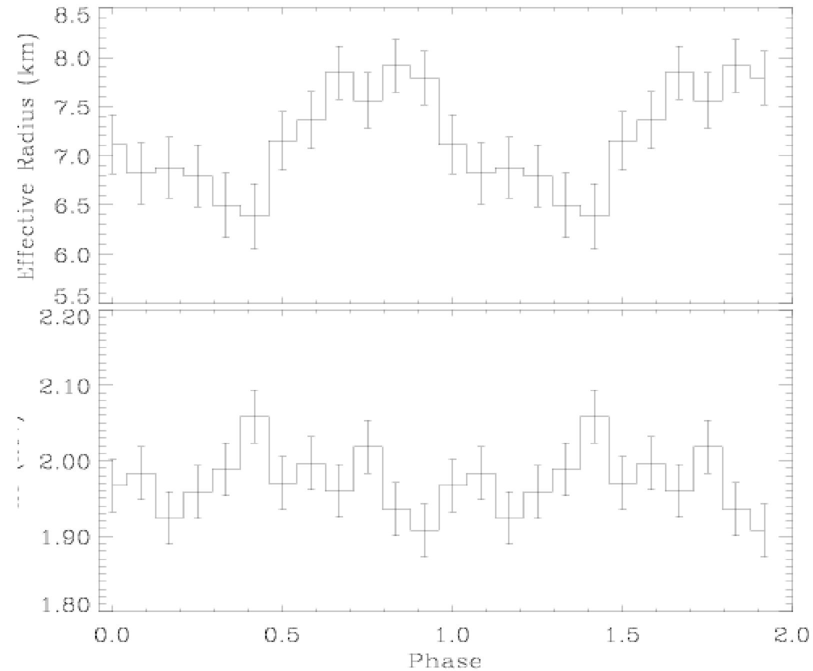


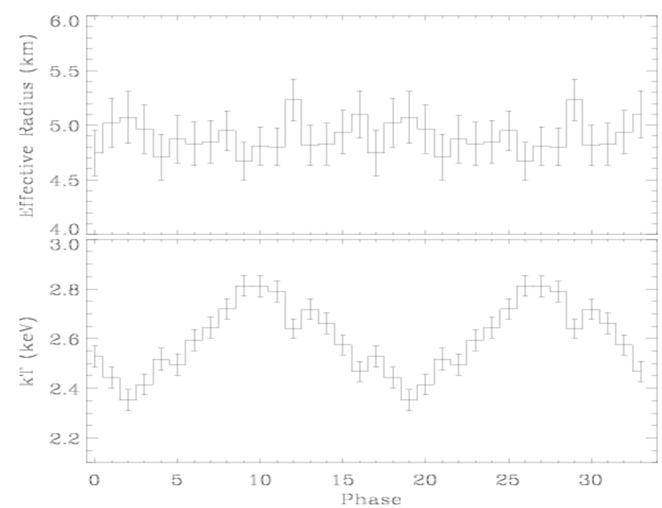
- New electron tracking detectors use photoelectric effect to measure X-ray polarization with high sensitivity.
- Direction of electron (and thus polarization angle) measured from the photoelectron charge cloud (Costa et al 2001; Black et al 2003).



Pulse Phase Spectroscopy: XTE J1814-338

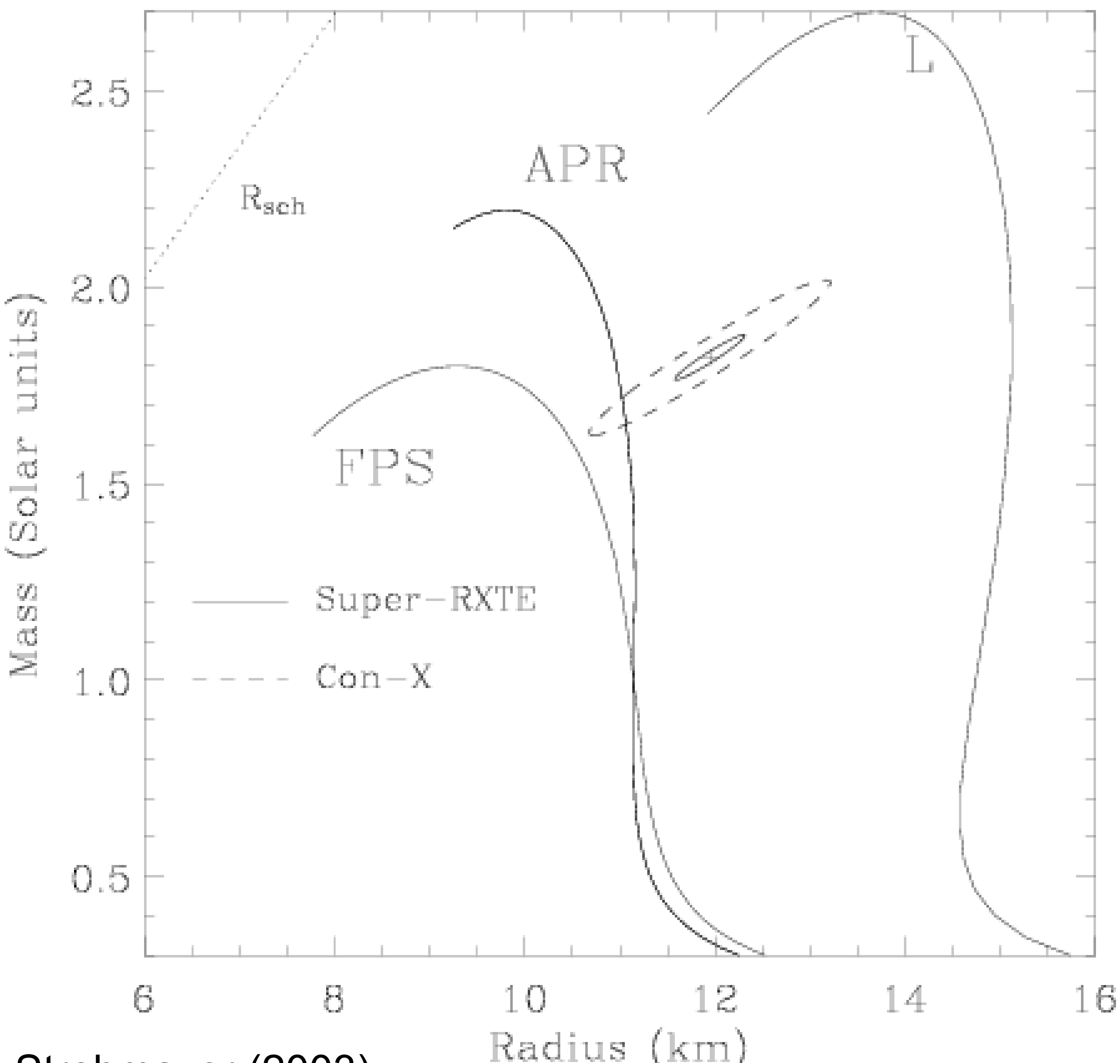






- Modulation consistent with varying projected area, at ~constant temperature
- This is not what would be seen from a “mode” where kT varied with some angular dependence

Burst Oscillations and M - R Constraints for Neutron Stars



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